Periglacial Features in Part of the

South-East Grampian Highlands of Scotland

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Thesis presented for the Degree of

Doctor of Philosophy of the University of Edinburgh

1976

In accordance with the University of Edinburgh Postgraduate Study Regulation 2.4.15;

I declare that this thesis was composed by me and is based on my own research.

ABSTRACT

The study examines the nature and distribution of periglacial lobes, terraces, gliding boulders, rockfalls and avalanches in granite and metamorphic terrains in a part of the South-East Grampian Mountains of Scotland. Areal variations in the weathering of granite boulders were also investigated.

Massive granite boulder lobes are extensively developed upon slopes in the Lochnagar and Mount Keen granite areas. The values of 14 parameters, established to describe the main elements of a lobe, were measured on 300 granite lobes. Various techniques were used to analyse the resultant data. Granite lobes are rare upon north-facing slopes, and absent from ground believed to have been covered by Loch Lomond age glaciers. It is concluded that these lobes are fossil features formed during the severe conditions of the Loch Lomond Stadial. Detailed sampling of 50 metamorphic lobes revealed that they are smaller features, largely restricted to the upper slopes of quartzite hills. Terraces are rare in both types of terrain.

Gliding boulders are common in the granite and metamorphic areas. The values of 15 parameters were measured on 200 metamorphic and 150 granite gliding boulders. The resultant data were analysed and compared. Individual boulder movements of up to 2cm/year were recorded between 1971 and 1975. Dendrochronological investigations of calluna and vaccinium plants growing in four furrows suggested that gliding boulder movements have decreased in the last 7 or 8 years.

Rockfalls are frequently released from the backwalls of the three Lochnagar corries, contributing to the extensive postglacial screes. Nine rockfalls were observed between 13 June and 1 August 1972. The largest fall involved almost 4 tonnes of granite boulders. Avalanches are common on snow accumulation slopes. Their erosional activity is restricted,

but they are efficient transporting agents.

Four techniques were used to investigate possible differences in the extent of weathering of granite boulders in sites 'inside' and 'outside' the mapped limits of four presumed Loch Lomond age corrie glaciers. The tests assessed the amount of edge and corner rounding of the blocks, and also the degree of surface and subsurface granular disintegration. All tests indicated that boulders 'inside' the presumed limits are marginally but consistently less 'weathered' than those in 'outside' sites, independently supporting the view that corrie glaciers occupied these sites.

ACKNOWLEDGEMENTS

I would like to express my thanks to my two supervisors in the Department of Geography, University of Edinburgh, for their assistance and encouragement during the preparation of this thesis. Dr J.B. Sissons provided valuable inspiration and advice throughout the project, and Dr R.P. Kirby introduced me to the analysis of numerical data. Thanks are also due to my fellow postgraduate students in the enthusiastic school devoted to Quaternary research, for valuable discussions and assistance.

Especial thanks to Mr D. Cruickshank (Edinburgh University Phonetics Department) and Dr R. Hipkin (Geophysics Department) for equipment and advice for the tape recorder weathering studies, to Dr G. Miller (Nature Conservancy Grouse Moorland Research Unit, Banchory) for suggesting the heather-stems dating technique, to Mr J.C. Donaldson of Braemar for weather information and sources, Mr E. Langmuir (Moray House College of Education, Edinburgh) for valuable discussions on avalanches, Mr J. Matthews of Edinburgh University (Geography Department) for computer advice, and to all the many other people who gave their time and advice.

I am indebted to the landowners, factors and gamekeepers of the Estates of Balmoral, Glen Tanar, Invercauld and Mar, for permission to visit the land freely, and for their assistance; also to several people of Deeside for their kindnesses and hospitality.

Finally I am deeply grateful to Anne Cameron for help and support during this project, and for the many hours sacrificed by Mrs E. Shaw in order to type this manuscript.

The research was financed by grants from the Natural Environment Research Council, which is gratefully acknowledged.

CONTENTS

FIGURES

PHOTOGRAPHS

CHAPTER 1

Introduction to the Study

Little quantitive information exists about the distribution, dimensions, contemporary activity and inter-relationships of periglacial features in the British Isles (see Chapter 2). The object of this study is to provide such information for a selected range of periglacial features occurring within a limited area of the south-east Grampian Mountains in Scotland.

As recently as 1958 R.W.Galloway presented a study whose primary purpose was stated as being "to show that periglacial conditions have prevailed in Scotland" (1958, p.2). That intense periglacial conditions once existed in Scotland and 'mild' periglacial conditions characterise the uplands today is now firmly established. There is still a dearth of fundamental knowledge of the range of periglacial features present, their distribution geographically and topographically, the sizes to which these features can develop, or have developed, under certain topographical and geological conditions, and their general form and nature. With the exception of the detailed study by R.B.King (1968), very little progress has been made in this direction since Galloway's (1958) pioneering work.

The present study describes the results of two summers' field investigations of boulder lobes, boulder terraces, gliding boulders, rockfall and avalanche activity and the weathering of granite boulders in a part of Aberdeenshire. The study area comprises the upland massifs of Lochnagar (1154m), Mount Keen (938m) and the hills around Glas Maol (1068m), which are all part of the Mounth range of the south-east Grampian Mountains. Broadly, the area is located between longitudes 2°55' West to 3°30' West, and between latitudes 56°50' North to 57°00' North (Map Figure 1.1). Lochnagar and Mount Keen are composed of fine- to medium-grained granite and Glas Maol of quartzite surrounded by schists (see Chapter 3). The close juxtaposition of the granite and metamorphic hills afforded an opportunity for

SITUATION OF THE STUDY AREA

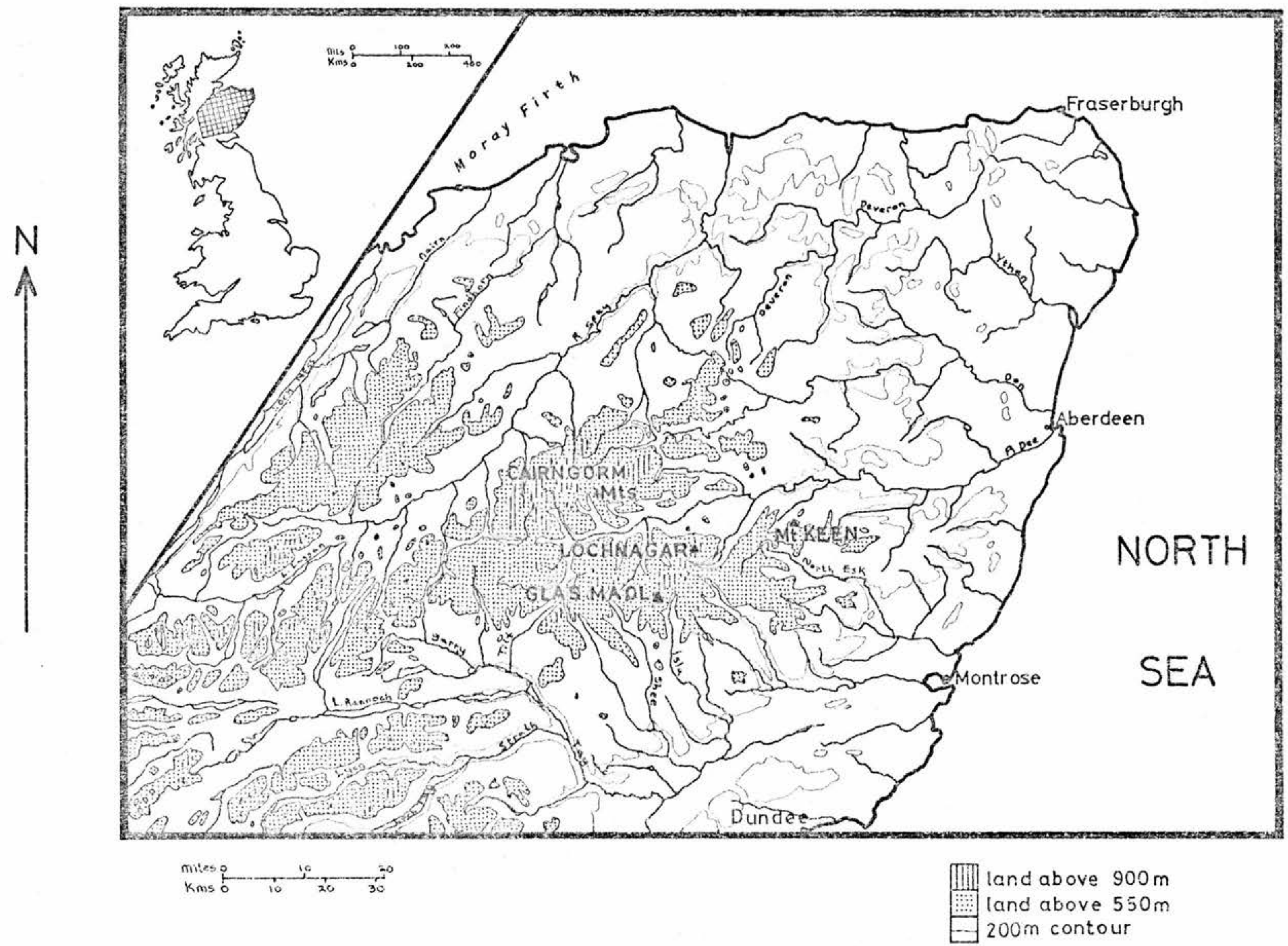


Figure 1.1

comparative studies to be made.

Initially the area was investigated upon 1:10,000 scale vertical aerial photographs using a binocular mirror stereoscope. This preliminary examination allowed the main glacial and periglacial features to be identified and delimited. The first field season began by ground checking the air-photograph interpretation, followed by detailed investigations of the main periglacial features of the area.

Large boulder lobes are a characteristic feature of this area, some of the finest examples in Scotland being developed upon the slopes of the Lochnagar massif (Galloway, 1958, p.132). These features were examined in great detail. A total of 300 granite lobes and 50 quartzite lobes were closely investigated and the dimensions and angles of their facets recorded as were the details of their topographic situation. The fabric pattern of the boulder risers was studied and boulder size sampling was also carried out.

Very few boulder terraces are developed in this area, but some were investigated and compared with the lobes.

Gliding boulders occur widely, being well developed in both the granite and metamorphic areas. Sampling was carried out in both terrains, 200 examples being examined in the metamorphic area and 150 in the granite area. Features of interest were the size and shape of the gliding boulders, the nature and length of the furrow, the size and disposition of the bow-wave, the alignment of the boulder and the characteristics of the slope upon which the feature occurs. The present day movement rates of gliding boulders were examined using wooden stakes driven into the soil as fixed reference points. An attempt was also made to assess the rate of gliding boulder movement over the recent past by dating the furrow at intervals along its length using the age information obtained from the woody stems of moorland plants growing in the furrow. Finally the various measured characteristics of the gliding boulders and their slopes were correlated in an attempt to assess the relative importance of the various factors affecting the movement of gliding boulders.

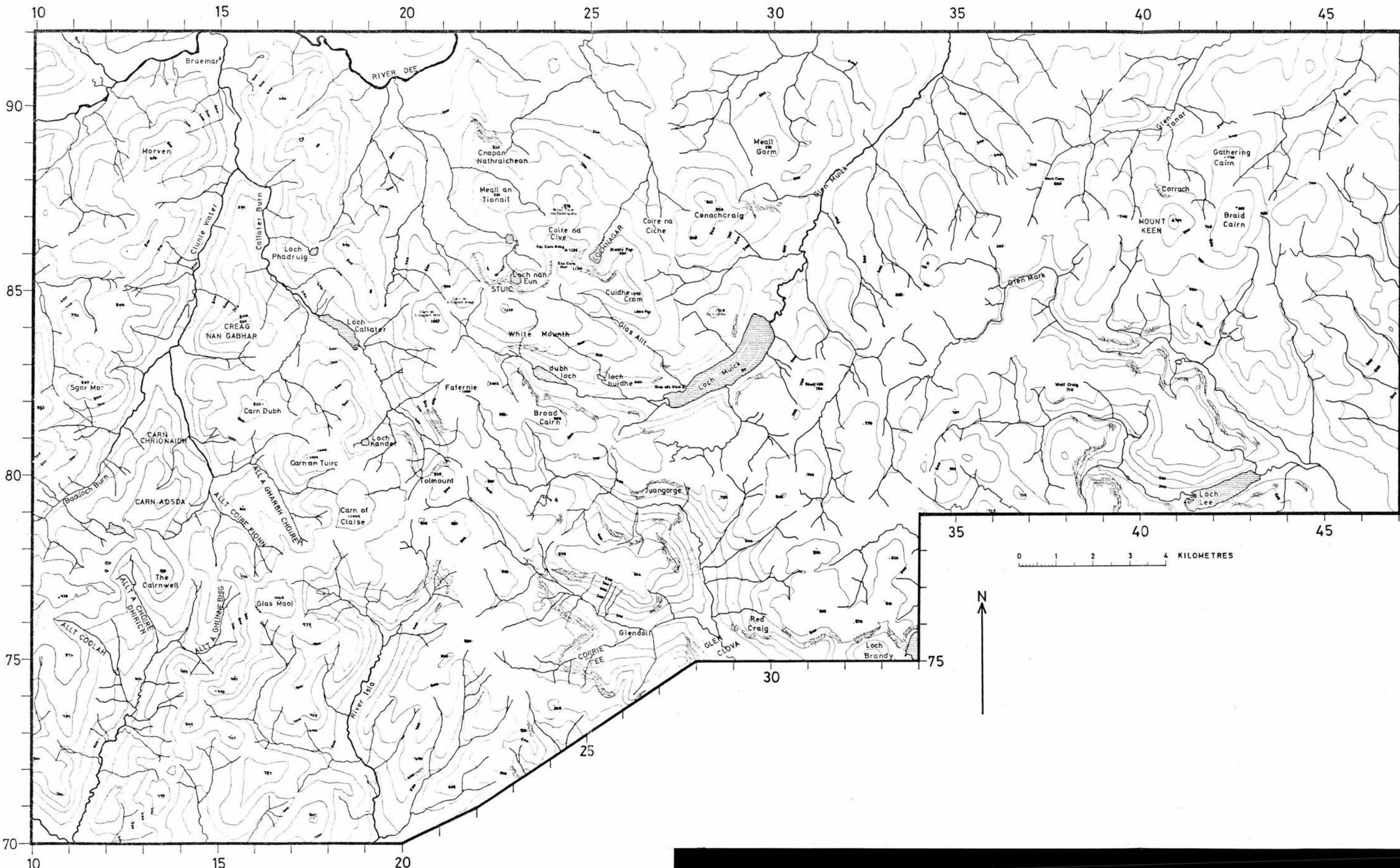


Figure 1.2

Physiographic detail of the South-East Grampian study area

Screes are well developed below the free faces in the study area. These were investigated for evidence of post depositional movement in the form of fabric patterns and size sorting. Several rockfalls were observed and investigated. The distribution and effects of avalanches were also examined.

The four corries in the granite areas each contain evidence of the former existence of corrie glaciers, with discontinuous arcuate moraines at their mouths and hummocky moraine deposits upon the corrie floors. The distribution of large boulder lobes was mapped in relation to the presumed maximal extent of these glaciers. Several techniques were used to investigate the degree of weathering of granite boulders situated upon the floors of the corries compared to the degree of weathering of those outside the presumed glacial limits. The aim of this weathering study was to investigate the possibility that the former existence of corrie glaciers could be established independently of the morphological evidence, and to develop a relative chronology based upon the differences in the degree of edge-rounding, granular disintegration and sub-surface weathering of granite boulders from sites 'inside' and 'outside' the presumed glacier limits.

The study begins with a detailed examination of the literature concerned with the periglacial phenomena of the British Isles (Chapter 2) followed by a description of the physical characteristics of the study area (Chapter 3). A discussion of the main frost action and mass wasting terms, and of the mass movement landscape forms (Chapter 4) precedes the presentation of the research results (Chapters 5 to 9).

CHAPTER 2

The Historical Perspective: An Outline of the Development of Periglacial Studies, with Special Reference to the British Isles

Introduction

"There exists in every province of science such problems and subjects which, having been for a time mere conjectures and suppositions, suddenly gain importance, arousing tremendous interest, or again sink imperceptibly into oblivion. In the field of geography and geology a typical instance of such vicissitudes is that of the history of periglacial problematics" (Jahn, 1954, p.117).

The last seventy years have witnessed several phases in the development of periglacial studies. Periglacial research has progressed rapidly in recent years as an understanding of the problems and the increasing precision of methods have shown the importance of the periglacial environment in the shaping of the present-day land forms in many parts of the world. These studies first came into vogue around 1910, when the important Eleventh Geological Congress was held in Stockholm. This was followed by an excursion to Spitsbergen allowing some of the conference participants to acquaint themselves with contemporary periglacial phenomena. A second phase of vigorous enthusiasm began just before the second World War, and still continues (Jahn, 1954). Periglacial studies received an impetus after 1945 with work by the Americans and Canadians in the tundra of Alaska and Canada, by the French, and notably in Poland where a group of workers were inspired by Jan Dylik and founded the international journal of periglacial geomorphology, the BIULETYN PERYGLACJALNY (Sparks and West, 1972, p.99). This second phase largely began with the strategic studies in the arctic north during the second World War, when particularly rapid advances were made.

Writing in the first issue of the BIULETYN PERYGLACJALNY, Dorywalski et al. (1954) believed that the study of the Pleistocene was entering a new evolutionary phase that could only be compared to the one that saw the birth of the idea of continental glaciation, such was the accelerated expansion of periglacial studies.

Early Historical Development

The history of periglacial research in the British Isles can be traced back to the acute observations and detailed descriptions in the writings of the early natural historians and geologists.

A century and a half before the term periglacial was coined Borlase (1758, p.76), writing about the natural history of Cornwall, and later Pryce (1778, p.124) and Mantell (1822), described deposits of superficial and unconsolidated material similar to that called 'Head' by De la Beche (1839). De la Beche reported a deposit of gravels resting upon the undisturbed Greensand of the Bovey Depression (1839, p.p.256-257), and a 'head' of angular fragments upon the raised beaches of the south-west of England. It is interesting to realise that De la Beche noted "there has been a great movement of the decomposed surfaces of the hills downwards, covering up all irregularities that presented themselves, and rendering the surface more smooth than would otherwise happen" (1839, p.432). Thus he described the results of gelifluction, a process about which he was unaware, and put forward what was later to become a key concept in the 'periglacial cycle of erosion' (Peltier, 1950; Birot, 1968).

Murchison (1839) described in great detail 'local drifts' from the flanks of the Woolhope Dome in the Hereford Basin, which were in fact, extensive head deposits consisting of interbedded angular heads of Silurian materials and lenses of red micaceous sands and silts.

Austen (1851) working in southern England, discerned that these superficial bedded accumulations of local material were the results of former processes. He was the first to recognise the connection of this 'head' with the glacial period, concluding that the 'head' had resulted from a long continued period of subaerial wasting under severe climatic conditions. Later Wood (1882) described the buried cliffs of southern England that had marine shingle at their bases, covered by a "peculiar terrestrial formation due to the atmospheric agencies of an arctic climate" (1882, p.718). He also discussed the permanently frozen soil of Siberia and the active layer produced by summer thawing, "the part below remaining frozen is impermeable by water so that, as this can have no escape vertically, it must convert the thawed layer into sludge, the tendency of which is to slide horizontally from higher to lower ground" -- almost the words of Andersson's (1906) later and better known definition of solifluction. Analogies were made with Coppinger's work in Patagonia where slippage of the soil cap was described as existing to an unparalleled degree due to the exceptionally wet nature of the climate (Coppinger, 1881, p.348). Wood also identified involutions on the Isle of Wight foreland and at Brighton, the beds presenting the appearance of having doubled back on themselves (p.720). He wrote about the action of intense frost splitting up flints and stones (p.720), and described pebbles in beds of clay that were set up vertically by frost, having originally rested horizontally in undisturbed beds (p.718).

Reid (1887) explained the origin of coombe rock, the gelifluction product of chalk areas. Contemporary soilcap motion caused by frost was recognised by Davison (1889), and he performed experiments to determine the mechanisms and rates of frost-induced creep processes.

James Geikie (1894) recognised the severe conditions of the 'extra-glacial tracts'. The areas never invaded by the great 'mer de glace', he pointed out, would have been unvegetated, and influenced by thick snow in winter and torrential water in summer, the saturated soil creeping, slipping and even flowing down the slopes. Evidence of the action of frost and thaw in southern England was described in the form of ruptured rock surfaces, accumulations of rock debris, coarse gravels, tumbled and confused subsoils, and sheets of sand loam and brickearth. He summarised the known occurrences of rubble drift, head, coombe rock, warp and trail in Britain, and discussed the action of frost and thaw in arctic regions, processes that he believed were responsible for these 'drift' deposits.

Thus the climatic significance of certain relict phenomena occurring in Britain was appreciated by a few early workers, but a detailed knowledge or understanding of the 'extra-glacial tracts' was limited and did not seem to gain widespread acceptance.

The Influence of Work Overseas

Periglacial research, as such, is usually deemed to have begun early in the twentieth century with the recognition of the extraglacial environment as a distinct morphogenetic zone and its identification by a universal term. Three workers were instrumental in describing the distinctive processes of the extra-glacial zone.

The important process of frost weathering in a freeze-thaw snow climate was first described in detail by Matthes (1900) who introduced the term NIVATION to identify this process. Perhaps the best known paper in the periglacial literature was published by Andersson (1906), a description of his observations of mass movement processes in the arctic climate of Bear Island. He proposed the name SOLIFLUCTION to describe these saturated mass movement processes associated with arctic areas. This process had been described 24 years earlier by Wood (1882) who had realised the role played by permanently frozen ground in this process, a factor that Andersson had not observed. The term PERIGLACIAL was formulated by the Polish geographer Lozinski (1909), a term that replaced the ambiguous 'sub-glacial' used by Andersson (1906) and others. Lozinski also set forth the concept of periglacial facies and gave the first coherent account of the characteristics and processes of the periglacial zone deduced from his observations in arctic areas. Lozinski discussed Andersson's theory, but believed that frost weathering was the essential characteristic of the periglacial environment. Nowhere in his writings, or Andersson's, was allusion made to the importance of deeply (perennially) frozen ground. Both writers seemed to be unaware of this phenomenon.

Matthes, Andersson and Lozinski were responsible for establishing a conceptual framework and introducing a terminology that served to focus attention upon the frost climates of the world. They only crystallised the descriptions and notions that had appeared in print, in Britain at least, long before their writings. A series of important papers appeared soon after these three works, each introducing new terms and concepts to the accumulating periglacial vocabulary, and describing features that had previously been unrecognised or at least undocumented. Significantly they all resulted from work in arctic areas.

Rock glaciers were identified in Alaska by Capps (1910) who devised this term to describe moving lobate streams of angular talus in certain arctic mountains. Cairnes (1912) described bench-like features, the surfaces of which were covered in angular frost debris, that were cut or built at intervals on hillslopes in Alaska and the Yukon. This process of differential erosion he termed EQUIPLANATION. Similar hillslope benches and flattened summits were ascribed by Eakin (1916) to a process he called ALTIPLANATION. The bench features he recognised were largely constructional, the material being derived from backwasting scarps and transported over the bench surface by frost creep processes. Hogbom (1914) produced the first comprehensive report upon the frost phenomena and patterned ground features in parts of Scandinavia and Spitsbergen. The role of permanently frozen ground became increasingly recognised as work in arctic areas continued. Capps (1919) emphasised the importance of permanently frozen ground in influencing 'soil flows' in Alaska, and described a range of features produced by slow and rapid soil flow processes upon a permanently frozen subsoil.

As original work in periglacial areas continued and new features were discovered and described, new terms proliferated. Parallel studies in various countries and different languages produced a confusing multiplication of terms. Bryan (1946) attempted to standardise periglacial terminology by producing a new vocabulary from classical roots. His scheme has achieved little success, the terms often being unwieldy and too unfamiliar to replace established terms. Further attempts to unravel the confusing mass of terms, and the complexities introduced by frequent overlapping of these, were made in the early issues of the Biuletyn Periglacjalny (eg. Dylikowa and Olchawik, 1954, 1956). Attempts at rationalisation of the periglacial vocabulary still continue.

Periglacial Features in the British Isles: A Summary of Present Knowledge

Studies of the newly described periglacial phenomena were slow to begin in the British Isles. This is partly because until quite recently it was widely believed that fossil periglacial phenomena in the formerly glaciated areas of the world were insignificant. European studies had concentrated upon contemporary phenomena on mountains and in the arctic, or on fossil features in the unglaciated areas of the continent. Dines *et al.* (1940) believed that periglacial deposits in Yorkshire occurred only outside the terminal moraine of the last glaciation. Subsequent work has shown that fossil periglacial phenomena associated with severe climatic conditions exist even in the area covered by the last ice sheet. Interest in the periglacial features of the northern part of the country developed during the 1950's. Most of the published work before the mid 1950's dealt with the southern part of the country, while later work was in the northern part, within the glaciated zone. As a result of this emphasis most of the earlier work dealt with head deposits, which are particularly noticeable outside the southern limits of glaciation, although they do occur less frequently within glaciated regions. Later work expanded not only its area of investigation, but also the range of features identified increased.

The present extensive knowledge of periglacial features and conditions in the British Isles can be most conveniently considered under the effects of wind, those induced by freezing and thawing in the soil including permafrost, ice wedges and patterned ground, thermokarst, frostcreep and gelifluction, the processes involved in frost weathering, the effects of snow patches, snow avalanches and fluviatile action.

Wind Action.

Periglacial wind action in Britain and Europe was responsible for deposits of loess and lesser areas of coversands, the formation of dunes and the development of some minor erosional forms.

Eolian periglacial deposits are derived by deflation mainly from areas of outwash, from the surface of glacial deposits left freshly exposed by ice retreat, from fine sediments deposited by proglacial rivers in periglacial areas, and from frost shattered rocks rich in sand and silt. Deposits formed by wind generally fall into two classes: well sorted sand which typically exhibits a dune form at the surface, and massive and well sorted silt. Eolian sands usually occur geographically near to their source, whereas eolian silts may be distributed over wide areas (Frye and Leonard, 1952). Loess and coversands are distinguished upon the basis of grain size, loess being predominantly of silt size, and coversands varying from fine to coarse sand. Loess is not usually stratified unless it occurs in wet depressions or ponds. The grain size may vary according to the distance of the deposit from the source, the finer deposits being farther away. Similarly the thickness of the loess blanket decreases away from the source (Ulrich, 1949; Ruhe, 1969).

Loess (or Löss) was discussed by Geikie (1894) and its known occurrences throughout Europe were described, but no mention was made of any deposits in Britain. At that time loess was thought to represent either the flood deposits of glacial times or a wind-borne deposit, views being sharply divided. Except for small patches in south-eastern England, loess is in fact comparatively rare in Britain, although it mantles thousands of square kilometres of lowland in eastern Europe and European Russia, mostly lying beyond the limits of the maximum glaciation. The less common occurrence and smaller deposits in Britain have been attributed (Zeuner, 1959) to the more oceanic climate of the British Isles.

A 3–4m thick deposit of interglacial loess was identified on the Durham coast early this century by Trechmann (1919) and Galloway (1958, 1961a) described the only known eolian deposit in Scotland, a 1m thick layer of gritty silt lying upon and derived from fluvioglacial material near Kinross. Otherwise loess has only been described from the central and southern parts of the country. Loess is becoming increasingly recognised as an important constituent of many of the soils of this area, usually occurring as a thin layer of weathered silty drift partly mixed with the underlying deposits (Perrin, 1956). Loess has been identified over a variety of geological formations, notably the Chalk of parts of the Yorkshire and Lincolnshire Wolds (Catt et al., 1974), the Upper Chalk and Clay-with-flints of the Chiltern Hills (Avery et al., 1959, 1969, 1972) and South Downs (Hodgson et al., 1967; Perrin, 1956), the Carboniferous Limestone of Derbyshire (Pigott, 1962) and Somerset (Findlay, 1965), the Bunter Sandstone of Nottinghamshire (Robson and George, 1971), the tills and glacial gravels of North Norfolk (Catt et al., 1971), and over the Cornish Serpentine (Coombe et al., 1956). The deposit formerly known as brick-earth has now been shown in many cases to be a true loess (eg. Pitcher et al., 1954).

Cover sands are almost unknown in Britain. Deposits similar to coversands have been described from the North Lincolnshire Wolds

(Straw, 1963) and the Vale of York (Matthews, 1970). The latter deposit exhibits a hummocky surface resembling fossil dunes, similar to the cover sands of the Netherlands. Across the North Sea cover sands are widespead in the Netherlands where fossil periglacial parabolic dunes and sand ridges have allowed the prevailing Pleistocene wind directions to be determined (eg. Maarveld, 1960; Rudberg, 1968; Seppala, 1971, 1972).

The importance of wind as an erosive agent compared with other geomorphic processes under periglacial conditions has not been established (Bird, 1969). Katabatic winds blowing from glaciers often carry outwash sands and may be capable of producing pits, grooves and facets on boulders (Blackwelder, 1929). Wind-driven snow and ice may be capable of eroding pedestal rocks (Sverdrup, 1938) especially as snow at low temperatures has the physical properties required for corrasion effects on hard rocks (Teichert, 1939), although the limited evidence of the erosive action of contemporary periglacial winds from some areas does not support these views (Pissart, 1969).

Ventifacts and wind polished stones are frequently left as residual pavements in the deflation sources, or in the path of silt bearing winds. Such pavements have been widely recognised in the Netherlands and Southern Sweden(eg.Johnsson, 1958; Schonhage, 1969), but only one example has been reported in the British Isles, from near Pontefract in Yorkshire (Edwards and Trotter, 1954). Periglacial ventifacts have been found in the Quaternary sequence of the north-east Cheshire basin (Thompson and Worsley, 1967), from the neighbourhoods of Manchester and Pendleton in Lancashire, and over wide areas of the East Midlands and Yorkshire south of the Escrick moraine (Raw, 1934; Edwards and Trotter, 1954), as well as farther north around Wakefield (Edwards, 1936; Bisat, 1946), and farther south in Worcestershire (Edmunds and Oakley, 1947).

The undercut stacks of sandstone on the millstone grit moorlands of Yorkshire have also been attributed to erosion by wind driven sand (Edwards and Trotter, 1954).

Frozen Ground Phenomena.

Perennially frozen ground in arctic regions is known as permafrost, a term suggested by Muller, (1947) for "a thickness of soil or other superficial deposit, or even of bedrock, of a variable depth --- in which a temperature below freezing has existed continually for a long time (p.3)". Permafrost exists as a result of a negative heat balance at the earth's surface. Muller recognised 'dry permafrost' in which moisture was not present in sufficient amounts to allow the development of interstitial ice to act as a cement, and 'frozen ground' where water was present, mostly in the form of ice.

An active layer may exist above the permafrost, this layer thaws when temperatures permit, and refreezes in winter during cold spells, or nightly. When thawed, this layer moves readily to a depth dependent upon a variety of factors such as the air temperature regime, insolation exposure, soil conductivity and the insulating effects of a snow or vegetation cover.

At the present day three zones of permafrost have been identified

1. Continuous Permafrost - where the severity of the present climate is able to form permafrost. Unfrozen areas occur largely beneath water bodies such as deep lakes, large rivers and the sea.
2. Discontinuous Permafrost - a zone in which unfrozen areas, or taliks, exist.
3. Sporadic Permafrost - the marginal zone of generally unfrozen ground in which small islands of permafrost occur.

Unfrozen ground exists below all permafrost at depth.

The identification of contemporary permanently frozen ground was made by many arctic expeditions, and its nature was reported from early engineering and mining projects in Russia, Siberia, Alaska and the Yukon. The first major scientific study of frozen ground was made in Alaska (Leffingwell, 1919) from where further work emerged during the second World War as the economic and strategic importance of the arctic and sub-arctic regions was realised. (eg. Taber, 1943).

Permafrost in the British Isles: The widespread existence of Pleistocene perenially frozen ground in Britain has been postulated since last century (eg. Reid, 1887, p.369; Wills, 1929; Zeuner, 1937), but few workers have associated fossil periglacial structures with the former existence of permafrost. Consequently, despite the fact that relict periglacial features have been described from the south-west of England for over 200 years, until recently little mention has been made of possible frozen ground conditions in this region, when Waters (1961) asserted that periglacial involutions and ice-wedge pseudomorphs, in the South-West, were certain indicators of former permafrost conditions.

According to Black (1969), ice-wedges are perhaps the only periglacial features truly indicative of their temperature of formation, and are diagnostic of permafrost (Washburn, 1973, p.93). In Alaska, Péwé (1969) determined the permafrost is present and can be formed where the mean annual air temperature is about -1°C, but a mean annual air temperature of -6°C to -8°C is required for ice-wedges to grow (Lachenbruch, 1962, 1966; Péwé, 1966a, p.78; 1966b, p.68; 1969).

As a result of such isolated and localised results several workers have drawn rather detailed climatic inferences from the presence of fossil ice-wedges in the British Isles. Thus, Williams (1969) suggested that during the coldest part of the last glacial period the mean annual isotherm of -6°C to -8°C must have lain across southern England, and extensive permafrost probably occurred in the lowlands approximately as far west as a line from Southampton to central Somerset, and on higher ground further west, possibly descending to about 275m on Dartmoor. Several earlier palaeoclimatic maps constructed by continental workers have shown the southern boundary of the permafrost zone, during the last glacial period, lying well to the south of the British Isles. (eg. Klute, 1951; Tricart, 1956; Wright, 1961).

The supposed distribution of permafrost within Britain during the last glacial period has recently been shown in map form (Williams, 1965). Former permafrost periods have been inferred from fossil ice-wedges in the sediments of earlier glaciations (eg. Waters, 1960; West, 1968a), at least four former permafrost periods having been suggested (West, 1969).

Many recent palaeoclimatic inferences have thus been drawn from the presence of fossil ice-wedges in the Pleistocene sediments of the British Isles. These conclusions assume that the results of observations in Alaska (eg. Péwé, 1966a, 1966b, 1969) are applicable to the British Isles. Such conclusions, with the present state of knowledge, are at the best speculative and need to be treated with reserve until much more is known about the range of environmental conditions in which the various types of ice-wedges can form.

Fossil Ice-Wedges and Patterned Ground: In 'frozen ground' type permafrost (Muller, 1947), water is present which manifests itself as ground ice. Ground ice forms range from pore fillings in sedimentary rocks to bodies of clear ice reaching 30m or more across. Ice may comprise up to 80% of the permafrost, by volume.

The main ground ice forms are (Embleton and King, 1968):

1. Soil Ice	a. needle ice (pipkrake).
	b. segregated ice.
	c. ice filling pore spaces.
2. Vein Ice	a. single veins.
	b. ice wedges.
3. Intrusive Ice	a. pingo ice.
	b. sheet ice.
4. Extrusive Ice	formed subaerially, as in the case of ice formed on river flood plains (aufeisen)
5. Sublimation Ice	formed in cavities by crystallisation from water vapour.
6. Buried Ice	buried icebergs, buried glacial ice, etc.

Ground ice occurring as vein ice and pingo ice leaves the most distinctive fossil features. Vein ice develops as vertical or near vertical sheets of ice from a few to many millimetres thick and reaching up to 10m or more below the surface. Ice wedges are thicker sheets of ice, up to 10m or more across at the ground surface, which taper downwards. Ice veins usually occur in groups that exhibit a surface network in a polygonal pattern.

Fossil ice-wedge casts were identified by workers earlier this century but were not recognised as such. For example, Marr (1919) described, cropping-out on the faces of pits near Cambridge, features that he concluded were "channels due to subterranean erosion". Paterson (1940), after studying ice-wedge features in Baffin Bay reinterpreted these same features as "frost cracks".King and

Oakley (1936) had previously identified ice-wedge casts in superficial deposits of the Thames Valley. Only four years earlier Dewey (1932, p.p.44-46) unknowingly drew and described fossil ice-wedges from Rickson's Pit, near Swanscombe, in the Lower Thames Valley. He called these features "solution pyramids".

The first known description of fossil ice-wedges in Scotland was published by Anderson (1940). He identified two fossil ice-wedge casts in pits south of Edinburgh. Both were filled with till, one being 2m long, the other a little over 3m long. A possible ice-wedge cast had previously been described by Robertson and Haldane (1937) in sandpits in the Kelvin Valley on the northern outskirts of Glasgow. They referred to it as a "dike-like" structure, filled with sand cemented by a magniferous mineral. The first examples reported from Ireland were referred to as "gravel dykes" (Kilroe, et al., 1908).

By the beginning of the 1950's, fossil ice-wedge casts were being increasingly recognised. Notes recording their identification appeared frequently in the literature (eg. Arkell, 1947; Chatwin, 1954; Fitzpatrick, 1956a; Te Punga, 1957; Common and Galloway, 1958; Galloway, 1956, 1961a; Rice, 1959; Coope et al., 1961; Gailey, 1961; Lewin, 1966; Worsley, 1966a, 1966b; Ranson, 1968; Gruhn and Bryan, 1969; Colhoun, 1971). Two very important identifications of giant frost-wedges, arranged as large-scale polygons, were made on the Tabular Hills of North Yorkshire (Dimbleby, 1952) and in the valley of the Worcester Avon (Shotton, 1960). The Worcester examples formed polygons up to 30m across. These are comparable in size with tundra polygons currently forming in contemporary permafrost areas (eg. Rapp and Annersten, 1969).

Only rarely are the ice-wedge casts seen in plan-form, exhibiting a characteristic polygonal pattern.

Contemporary, small-scale, patterned ground resulting from frost sorting has commonly been reported from the hills of the British Isles. Small scale stone polygons and circles (up to about 1m diameter) of recent origin have been observed upon the uplands in the west of Scotland (Simpson, 1932; Godard, 1959), Rhum (Ryder and McCann, 1971), Skye and Mull (Godard, 1959), Shetland (Spence, 1957), the Cairngorms (King, 1968, 1971; Sugden 1970a, 1971), the Lake District (Hollingworth, 1934), northern England (Tufnell, 1969), and parts of Wales (Pearsall, 1950;Tallis and Kershaw, 1959; Ball and Goodier, 1970; Potts, 1971).

Small-scale frost-sorted stripes and frost-heaved striped ground have been reported from similar areas, notably the West of Scotland, Skye and Mull (Godard, 1959), Rhum (Ryder and McCann, 1971), the Shetlands (Spence, 1957), the Cairngorms (King, 1968, 1971; Sugden, 1970a, 1971), central Scotland (Miller et al., 1954), the Lake District (Hollingworth, 1934; Hay, 1936, 1937, 1942; Caine, 1963), and Wales (Goodier and Ball, 1969; Ball and Goodier, 1970).

Larger scale fossil examples of boulder stripes and circles have been less frequently described. They occur most extensively in the lowlands of the southern part of the British Isles (eg. Morgan, 1971), especially in the Breckland area (Watt, 1955; Watt et al., 1966; Williams, 1964; Chorley et al., 1966), although they have been identified upon summit areas and slopes in the mountains of Wales (Ball and Goodier, 1968, 1970; Foster, 1970), the northern Pennines (Tufnell, 1969), the Cairngorms (King, 1968, 1971; Sugden, 1970a, 1971) and Ben Wyvis (Galloway, 1961b), Dartmoor (Te Punga, 1956; Waters, 1965) and Northern Ireland (Colhoun, 1971).

Thermokarst: Thermokarst or ground-ice karst are terms given to topographic depressions which result from the thawing of ground-ice. There are many kinds including linear and polygonal troughs formed when ice-wedges thaw, collapsed pingos, thaw lakes and alases. Alases are thermokarst depressions with steep sides and flat grass-covered floors.

In the British Isles fossil pingo forms have only recently been identified with any certainty. Collapsed pingos may occur as shallow, roughly circular depressions. They may or may not have a raised rim. The name was proposed by Porsild (1938).

The first published study of pingos in the British Isles described a group of pingos situated east of Llangurig in central Wales (Pissart, 1963). Within the last few years several examples of pingos have been identified from many parts of the British Isles, notably from central and west-central Wales (Watson, 1971, 1972; Watson and Watson, 1972), the Isle of Man (Watson, 1971), East Anglia (Sparks et al., 1972) and Southern Ireland (Mitchell, 1971). The examples from East Anglia were non-committally termed 'ground-ice depressions', but were of thermokarst origin.

It is envisaged that the Welsh examples are of the open-system or East Greenland type, occurring in mutually interfering clusters (Watson, 1971). The open-system type of pingo was first described by Leffingwell (1919). It is also known as the hydraulic type as the theory of origin proposes a down-freezing of water-saturated surface sediments that would affect ground-water flow and cause an increase in sub-surface pressure. A sufficient increase in pressure would cause bulging of the ground. The other type of pingo, the closed-system, or Mackenzie type is believed to begin to form (Mackay, 1962) by the silting up of an open lake situated in a permafrost zone. The lake ice eventually freezes to the bottom and freezes the capping sediments, effectively sealing the unfrozen ground below the former lake and producing a closed-system. With the insulating effects of the lake removed, the ingrowing of the surrounding permafrost expels pore-water from the unfrozen sediments and creates a bulge at the surface as the pressure is relieved. Bostrom (1967) has suggested that the Mackenzie type are really of the hydraulic type, as the Mackenzie delta is an area of slow subsidence in which new sediments accumulating at the surface are being frozen onto the permafrost layer, while the base of the permafrost zone is melting as it descends. This creates a hydraulic pressure in the sub-permafrost layers which may be relieved by water rising through a crack or weakness in the rigid permafrost layer to form a pond. Sedimentation of the pond will cause it to freeze to its base in winter and a continued artesian rise will dome up the ice and sediments to form a pingo.

Much more work upon contemporary pingos is required before the modes of formation are clearly understood and before fossil European examples can be certainly ascribed to any genetic classification.

Frost Creep and Gelifluction: Together these processes are responsible for the downslope movement of rock debris in periglacial enviroments. The distinctive roles of the two processes are often hard to distinguish in the field (see chapter 4).

Frost creep and gelifluction deposits can occur on gradients as low as 2^{o}. They are classified according to their topographic form, as gelifluction sheets, gelifluction benches or gelifluction lobes. The deposits often show some crude stratification parallel to the slope, and mainly contain angular fragments. Included stones are characteristically oriented in the direction of movement.

Gelifluction deposits were the first periglacial phenomena to be recorded in the British Isles, gelifluction sheets being variously referred to as head, warp, trail, coombe rock, downwash gravel and Taele gravel. They are still the most commonly cited periglacial evidence.

Less attention has been given to the bench- and lobe-like forms occurring upon the uplands of parts of Wales and Scotland.

At the beginning of this century Officers of the Geological Survey described the long bench-like forms, paralleling the contour, on some of the Scottish Hills (eg. Peach et al., 1912, 1913; Crampton et al., 1914). They discerned that they were formed as a result of 'soil creep', acting upon frost-shattered fragments termed 'plateau frost debris'. Similar 'bench-like forms' or 'solifluction terraces' were identified by different workers in the Lake District (Hollingworth, 1934; Hay, 1937, 1942) and later in the Cairngorms (Watt and Jones, 1948; Metcalfe, 1950; Galloway, 1958), Shetland (Spence, 1957), Rhum (Clark, 1962; Eggeling, 1964; Ryder and McCann, 1971), and Wales (Crampton and Taylor, 1967; Watson, 1969a, 1970; Lewis, 1967, 1970; Ball and Goodier, 1970).

Gelifluction lobes have been less frequently reported from the British Isles. They were initially known as 'garlands' (eg. Hay, 1942), and rather confusingly often described as terraces or terraced debris with lobate-fronts, crescent-shaped banks or as oval terraces (eg. Hollingworth, 1934; Metcalfe, 1950). A very comprehensive study of the distribution of lobe-type features in Scotland was made by Galloway (1958). This study also included valuable qualitative descriptions of the types of rocks which made up the lobes, the nature of any vegetation cover, the general size ranges and slope angles of lobes and the nature of their sites. This study was followed by a more detailed investigation, concentrating upon the Western Cairngorm mountains, by King (1968).

Lobes of various types were mapped, measured, described and individuals were examined in detail.

Gliding boulders are a special kind of frost creep and/or gelifluction deposit (Washburn, 1973). They are isolated stones or boulders which are situated upon the regolith of a slope, and which leave a linear depression upslope and form a low mound downslope as a result of their relatively rapid movement.

Few studies of gliding boulders have been published, although they occur frequently in this country. Once again they appear to be restricted to the upland parts of the British Isles, above about 450m in northern England (Tufnell, 1969). They have been reported from various parts of Scotland (Galloway, 1958), in particular from the Cairngorm Mountains (King, 1968; Sugden, 1970a) and the Southern Uplands (Galloway, 1958; Tivy, 1962), and also from the Lake District (Hay, 1937, 1942; Johnson and Dunham, 1963), the Northern Pennines (Tufnell, 1969, 1972) and North Wales (Goodier and Ball, 1969; Ball and Goodier, 1970).

Frost Weathering.

Frost weathering is considered to be synonymous with frost wedging (Howell, 1962, p.197). It is the mechanical disintegration of earth materials by frost action (see Chapter 4), the prying apart by ice upon freezing. Bryan (1946) used the term congelifraction.

Frost wedging acts upon rock outcrops and surface debris to produce mountain-top detritus and boulder fields, and is considered to be capable of cutting erosion terraces or altiplanation terraces upon hillsides, and of producing tors. The frost weathering of cliffs produces screes and causes rockfalls.

Summit block fields in the Lake District were described by Yates (1830-1) and Marr (1916), who recognised their frost controlled origin, as did Geikie (1894) in his general treatment. Later workers have confirmed the existence of block fields in various parts of Scotland (Galloway, 1958, 1961b), Rhum (Clark, 1962; Ryder and McCann, 1971), the Southern Uplands of Scotland (Ragg and Bibby, 1966), the Cairngorms (King, 1968; Sugden, 1970a, 1971), the Lake District (Hay, 1942), Northern England (Tufnell, 1969) and Wales (Ball and Goodier, 1970; Potts, 1971).

Very few examples of altiplanation terraces have been located in the British Isles, and nearly all of these from the south-west of England (except King (1968) in the Cairngorms). They have been described from coastal Devonshire (Guilcher, 1950), and Dartmoor (Te Punga, 1956, 1957; Waters, 1962), Exmoor (Waters, 1962), and other parts of south-west England (Cotton, 1951; Waters, 1965). Several authors have discussed the role of frost weathering in the production of residual rock tors, notably Palmer and Nielsen (1962-Dartmoor), Palmer and Radley (1961- the Pennines), Waters (1962, 1965-South-West England) and King (1968 - the Cairngorms).

There has been almost no work done on the role of frostweathering in producing rock falls and screes in the British Isles. Much work remains to be done upon the rate of cliff recession caused by frost action, the timing of rockfalls and their triggering (eg. Prior et al., 1971) and the nature of rock fall screes (see Chapter 8).

Snowpatches.

Snow-patches are almost stationary bodies of snow on level or low-angled surfaces, which erode largely by nivation. The term nivation was introduced by Matthes (1900) who studied the effects of snow patches in Wyoming. Nivation was further understood after the work of Lewis (1936, 1939) in Iceland, and McCabe (1939) in West Spitsbergen, as largely accomplished by freeze-thaw action. Other workers have suggested that chemical weathering is promoted under snow-banks (Williams, 1949), that runoff from melting snow-patches accomplished perhaps more erosion than the patch itself (eg. Rockie, 1951), although Lewis (1939) showed in Iceland that meltwater acted more in a transporting capacity, and that snow-melt promoted increased gelifluction below snow-patches (Patterson, 1951).

Nivation by snow-patches produces nivation hollows. Three main types have been recognised (Lewis 1939), namely transverse, longitudinal and circular, dependent upon their orientation with respect to the direction of slope.

Late-lying snow-patches are a common feature of the uplands of the British Isles, frequently lingering until late-June (Scott, 1964; Graham, 1969; Clark, 1970). They usually occur upon north-to easterly-facing slopes where thick snow-blankets build up after redistribution by the prevailing Westerly winds. Characteristically they occupy positions a little below hill crests or noticeable breaks of slope and are associated with depressions and scoops in the ground (Clarke, 1970). Later on in the summer season accumulations of dirt often cover the surface of snow-patches, possibly derived by wind transport, slope wash from above, or the debris from the erosion scarps which frequently occur at the upslope edges of the hollows. The debris may be arranged in polygonal patterns upon the surface of ablating snow-patches (eg. Richardson, 1951, 1954; Ball, 1954; Richardson and Harper, 1957; Scott, 1964).

Prolonged snow-lie is favoured by several types of landform, including slope benches, natural ground hollows, solution hollows, and in the furrows of gliding boulders (Tufnell, 1971, 1972). Observations from the Northern Pennines (Tufnell, 1971) and the Cairngorms (King, 1968) suggest that contemporary snow-patches are found in these situations, and show evidence of erosive action, especially at the upslope edges of the hollows. Below the snow-filled hollows micro-gelifluction features, in the form of terraces and gliding boulders, are often seen to be promoted by the saturation produced by the slow melting of the patches (eg. King,1968).

Snow patches are believed to be capable of eroding benches upon hillslopes (eg. Gregory, 1966). These may be the beginnings of larger altiplanation terraces (eg. Guilcher, 1950), which are further developed by mechanical weathering (see Frost-Weathering section).

At the foot of steeply inclined snowpatches banked up below free faces or actively eroding steep rocky slopes there often exists a ridge of debris. They are known as pro-talus ramparts. Pro-talus ramparts have been observed in Wales (Watson, 1966) in Cwm Tinwen below a former snow patch inclined at about 26°.

Snow Avalanches.

Avalanches are broadly classified into two types, snow avalanches and mixed avalanches. The former are composed almost wholly of snow, the latter consist of snow mixed with a substantial amount of rock debris.

Flow is the dominant mode of movement, although some avalanches may begin as slab avalanches in which case sliding is the first process. They are a sudden, catastrophic event, characterised by a very rapid movement, of between 1 to 100 m/sec (Washburn, 1973).

Avalanches largely act in an eroding and transporting capacity, producing long, narrow avalanche chutes, or clearing wide zones of hillsides of their trees, loose rock and soil. The transported debris may be carried far from the base of the slope (eg. Crandell and Fahrestock, 1965), or be deposited at the foot of the slopes as avalanche boulder tongues (Rapp, 1959) or on the slope as debris-tails (Rapp, 1959; Potter, 1969) (see Chapter 4).

Very little has been recorded about the incidence of avalanches in the uplands of the British Isles, and what few records there are are confined to climbing guides and journals (eg. Smith, 1962, 1965; Fyffe, 1971; Langmuir, 1968, 1969; MacInnes, 1969) or to less specialised books and articles (eg. Fraser, 1966; Weir, 1973). The geomorphological effects of avalanches in the British Isles have received little or no attention.

Fluviatile Action.

Fluvial action in the periglacial environment is uniquely influenced by frost-action. Rivers are affected by the presence of permafrost, a thick ice-cover in winter, and proximity to geliflуction slopes and frost wedged debris.

Under the periglacial regime streams have a short period of flood following the general thaw. It is during this flood that a large part of their annual load is transported. Flood plains are aggraded to steeper slopes than under temperate conditions. When the climate ameliorates these deposits are dissected to produce unpaired terraces, and tributary streams become entrenched in their fans (eg. Watson, 1969b - South Wales).

In arctic regions aufeis and break-up phenomena are important. Aufeis are sheets of freshwater ice, usually formed either by a stream overflowing its banks during freeze-up or by ground-water coming to the surface in natural seepages and springs. These sheets are usually layered parallel to the surface of deposition, and when buried by later deposits form an important element of the stratigraphy. During the spring ice breaks up along river courses. It is usually accompanied by floods, especially as a result of downstream ice jams. The downstream flow of ice can cause gouging and erosion of the banks and floodplain during floods and leave ice-rafted stones, striated stones, ice-shove indentations and ridges, and stone-pavements. It can also severely disrupt vegetation.

Asymmetric valleys are commonly developed in periglacial areas. They have one slope steeper than the opposing one, possibly caused by the preferential thaw of permafrost on the slope with a more southerly aspect, which results in increased stream erosion at the base, or the pushing over of the stream due to increased gelifluction accumulation at the slope foot. It has been shown from Alaska that denudation caused by gelifluction and creep can be two or three times greater on south-east facing slopes than on north-west facing slopes (eg. Everett, 1967).

Break-up phenomena or fossil aufeis have not been identified in the deposits of the British Isles, perhaps as they would be expected to become almost obliterated by subsequent deposits. Several authors have alluded to the asymmetry of various valleys in Britain (eg. Kellaway and Taylor, 1952; Williams, 1968) and examined the variation of slope angle in relation to the aspect of the slope (eg. Gregory, 1966).

The features of periglacial fluvial activity that have received the most attention in the British Isles are the dry-valleys or dells. These are river valleys now devoid of streams. Dells are characteristically small and shallow with gentle slopes and generally a U-shaped cross profile. They have long been recognised in Britain as a feature of disequilibrium (eg. Reid, 1887; Geikie, 1894, p.p.395-396; Bull, 1940). Dry valleys originated by linear stream erosion and/or mass wasting in areas where sub-surface drainage was inhibited by permafrost or seasonally frozen ground. The process was accompanied by the production of abundant debris. When the climate ameliorated it is supposed the drainage infiltrated to some depth below the surface. A periglacial theory of origin is not completely accepted. Other theories include solution (in chalk and limestone areas), beheading of streams, and especially a formerly greater precipitation to produce copious runoff (eg. Dury, 1965, C15-C40).

Applied Periglacial Studies.

Periglacial studies assist not only geography and geology, but also palaeoclimatology, soil science, palaeobotany, palaeozoology, archaeology (eg. Williams, 1973), prehistory, mining, and engineering. Each of these diciplines is assisted by and contributes towards periglacial research.

An understanding of the processes active in the periglacial environment is vital to a rational development of the northern arctic areas since the entire history of man's exploitation of marginal environments - tropical rainforest, deserts, tundra , has been to apply middle latitude technology and approaches to land utilisation (Price, 1972, p.1). Perhaps the most advanced country is the Soviet Union with experience ranging from the construction of the Trans-Siberian railway at the turn of the century, to the planning and building of Norilsk and other modern towns in areas of permanently frozen ground (Cooke and Doornkamp, 1974). It is in fact after the costly experience of the Russian engineers that engineers elsewhere realised that the natural phenomenon of frozen ground needed to be fully understood and the forces correctly evaluated (Muller, 1947).

Permafrost engineering is becoming increasingly important as the marginal lands are developed for their natural resources. Most of this interest is in permafrost areas, which at present cover about 22% of the land area of the Northern hemisphere (West, 1968b). Before mining settlements can be established much preliminary survey and investigation is required to discover potential building sites (eg. Bird and Bird, 1957), potential harbour and air base sites (eg. Gajda, 1964), and to assess the problems posed by permafrost regarding the cost effectiveness of mining and removing the ores (eg. Ives, 1961, 1962). Such are the problems that it may be cheaper to lay a pipeline by a longer route than to cross permafrost areas (eg. Bulatov, 1972).

The vast reserves of the northern areas necessitate the solving of many complex, natural and economic problems including low winter air temperatures and the presence of permafrost, the scattered pattern of settlement and lack of communications (Krotov, Pomus and Rikhter, 1960).

The presence of permafrost is an obstacle to the development of any territory (Suslov, 1947).

Over the last decade engineers have become increasingly aware of the influence that periglacial processes have had upon the stability of soils and rocks in the temperate areas of Britain and Europe. Recognition of these effects has been largely due to increasing research and constructional experience in countries with cold boreal and tundra climates (Higginbottom and Fookes, 1970, p.85).

Valley-side bulging, cambering and gulling were first described from the Northamptonshire Ironstone field (Hollingworth, Taylor and Kellaway, 1944). These phenomena have considerable influences upon the engineering stability of this and similar areas, especially in the construction of reservoirs (Higginbottom and Fookes, 1970, p.102). The Zermanice Dam in Czechoslovakia was threatened by repeated bulging of the valley, emphasising a weakness developed in the Late-Pleistocene (Zaruba and Mencl, 1969, p.p. 74-76).

Frost-shattered bedrock increases the deformity and permeability, and reduces the bulk density of the surface layer (Higginbottom and Fookes, 1970, p.90). Chalk often shows frost-shattering to 30m depth and harder rocks, such as the Borrowdale volcanic series, have been shattered up to depths of 12-14m. The reduced loading capabilities of frost-shattered rock compared with the undisturbed parent necessitates the design and use of special foundations. A deep frost-shattered regolith poses special engineering problems in eastern and central European countries (Zaruba, 1952).

Large-scale landsliding and foundering is a widespread Pleistocene phenomenon that has a profound influence upon engineering works. For instance, the city of Bath owes much of its present layout to the distribution of rotational slides in the Midford Sands and underlying Lias Clays (Kellaway and Taylor,

1968). Many of the unstable areas within the city boundaries are maintained as public open spaces. Disturbances began in the mid-Pleistocene times and continued in the late-Pleistocene. Beyond the limits of glaciation in southern Britain, oversteepening of slopes stabilized by permafrost occurred by frost-sapping along the base and gelifluction in the active layer of the permafrost (Higginbottom and Fookes, 1970, p.105) over much of the south of the country, posing problems similar to those of Bath. Examples have been described from south-west Dorset (Brunsden and Jones, 1972), the Stroud district of Gloucestershire (Ackerman and Cove, 1967), the London Clay cliffs in the Thames estuary coast-lands (Hutchison, 1967), the lower Greensand of Surrey (Gossling, 1935), and much of south-eastern England (Weeks, 1969), as well as parts of the East Midlands (Chandler, 1970).
Other periglacial phenomena such as hill creep, ice wedges and involutions, frost mounds, and various sorted and unsorted soils have characteristic geo-technical properties that can profoundly influence the course of, siting of, or cost of engineering projects (see Higginbottom and Fookes, 1970).

In conclusion it is pertinent to point out that it is not only major engineering projects that can be adversely affected by a lack of knowledge of periglacial phenomena. The Ordnance Survey has unwittingly sited Ordnance Survey Bench Mark 2569.1 ft on the western slopes of Knock Fell in the northern Pennines upon an active gliding boulder (Johnson and Dunham, 1963). It is to be expected that this error will cause anomalies during any future re-surveys!

Conclusions

The foregoing, albeit brief, survey of the development of periglacial geomorphological studies has indicated the rapid advances made in the British Isles during the last twenty years. As recently as 1958, Galloway set out to "show that periglacial conditions have prevailed in Scotland (1958, p.2)". It is now widely recognised that periglacial conditions existed in all parts of the British Isles during certain stages of the Pleistocene, and that 'mild' periglacial conditions exist at present in some of the upland areas.

What is required today is an extension of the identification of a wide range of periglacial features in order to assess the factors underlying their distribution, but also detailed examinations of many individual features from a variety of situations to deepen our understanding of fossil and contemporary phenomena in this country. Combined with these investigations, parallel studies in present 'cold' periglacial regions are necessary. An understanding of the genesis of all periglacial features is now being sought, to replace the more superficial morphological descriptions and generalisations possible at present.

"The primary problem in (Scottish) periglacial studies is simply the acquisition of more information" (Galloway, 1958, p.258).

CHAPTER 3

GEOLOGY

3:1.

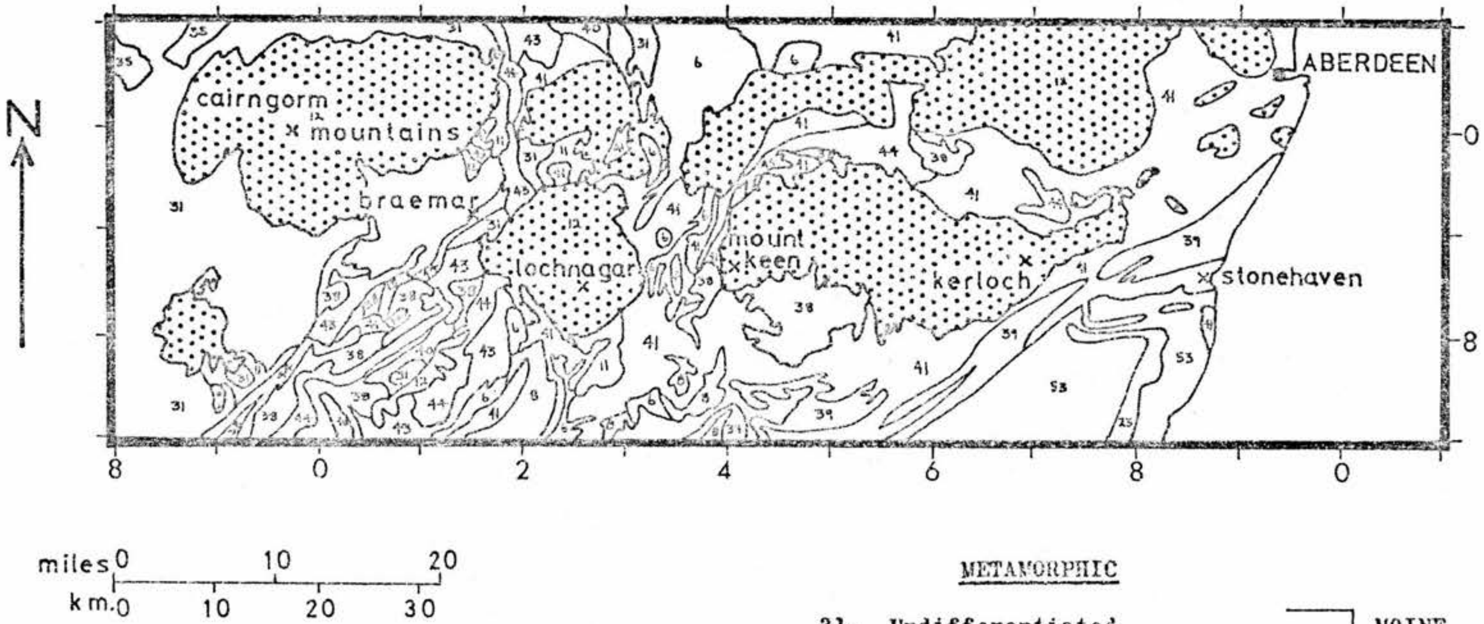
The study area is composed of a complex of metamorphic rocks penetrated by numerous granitic and other igneous intrusions, the most important being the Lochnagar and Mount Keen granite masses.

In the Grampians as a whole the metamorphic rocks consist of two main groups, a lower group of Moinian age (late pre-Cambrian) and an upper group of Dalradian age (late pre-Cambrian to late Lower Cambrian), which are essentially conformable (Johnstone, 1966). These rocks are paraschists. They represent part of a thick accumulation of sedimentary rock deposited on an Archaean Basement in a complex mobile belt (which stretched at least from Scandinavia to Ireland), the Caledonian Geosyncline. The Moinian rocks are uniform over a great vertical thickness and were probably shallow-water deposits of a slowly subsiding area during early phases of movement in the mobile belt. A considerable vertical variation of diverse rocks characterises the Dalradian sequence, which perhaps represents the sediments of the later more rapidly subsiding geosyncline.

During the 'Caledonian Orogeny' the rocks of the geosyncline were folded, a polyphase event, producing the Southern Grampians Nappe Complex and a deep sliding-surface below. The rocks of the Grampian Highlands are metamorphics of the 'Early Caledonides' of pre-Silurian age. Igneous rocks are associated with this orogeny, as pre-, early-, late-, and post tectonic intrusives and extrusives. The large granite masses are late- and post-tectonic plutons whose intrusive activity extended into lower Old Red Sandstone times, about 390-405 million years ago (Riddler, 1967).

The hills of the Cairnwell and Glas Maol area of Upper Glenshee are composed of Perthshire Quartzite and Cairnwell Quartzite (part of the Schiehallion Quartzite Group) of the Upper Group (Dalradian age). They are fine- to medium-grained rocks, compact and non-schistose (Law, 1961, p.23). A 'porous

GEOLOGY OF THE DEE VALLEY REGION



IGNEOUS

6.	Epidiorite & Hornblende Schist	DALRADIAN & MOINE
8.	Foliated Granite	
11.	Diorite	INTRUSIVE
12.	Granite, Syenite, etc.	
15.	Felsite, Trachyte, etc.	
23.	Old Red Sandstone - Andesite & Basalt Lavas	EXTRUSIVE

METAMORPHIC

31.	Undifferentiated	MOINE
35.	Limestone	
38.	Quartzite	DALRADIAN
39.	Schistose Grit	
40.	Slates, Phyllites & Mica Schists	
41.	Quartzose Mica Schist	
43.	Graphitic Schist & Slate	
44.	Limestone	
53.		LOWER O.R.S.

Figure 3.1

modification' due to alteration (Kaolinisation) of the feldspar grains is present, but otherwise the rocks are hard and resistant both chemically and mechanically. To the south of and between the quartzite outcrops occurs a complex pattern of Blair Atholl Dark Schists, Blair Atholl Calcareous Schist and infolded non-calcareous mica schist (the 'undifferentiated schist' of the Geological Survey). The Dark Schists contain quartz pods and are garnetiferous. Carbonaceous matter in bands traces out the schistose structure, and mica-rich bands alternate with the quartz-rich bands. A large amount of biotite mica is contained in the quartose bands. The Calcareous Schists are very compact metamorphic rocks with smooth planes of schistosity and appear flaggy. Much chloritized hornblend is a common constituent, and quartz defines the schistosity. Angular magnetite grains and zoisite are plentiful. The rock is almost an amphibolite. Finally, the infolded calcareous mica-schists are a quartz-muscovite-biotite-garnet-schist with a silvery sheen, and are associated with a crumbly, limy, banded rock of similar mineralogy but of different texture. Mica layers occur along the schistosity and garnet is present, intergrown with the quartz.

To the north of the Cairnwell the hills studied were Carn an Tuirc, Carn of Claise and Carn Aosda, which are also composed of quartzite. The quartzite of Carn an Tiurc is slightly impure and banded (Downie, 1954, p.26).

The metamorphic rocks are of sedimentary origin. Barrow (1893, p.351) found no evidence in their mineralogy or structure to suggest that they could have been formed of crushed igneous material. During the late phases of the geosynclinal episode the sedimentary pile would have rooted deeply into the earth's crust. Resulting lateral compression distorted the sediments into large and complex folds (Riddler, 1967, p.67). Heating at the base of the sedimentary pile caused metamorphism of the geosynclinal sediments. These movements were associated with igneous activity.

The degree to which the rocks have been metamorphosed indicates that the metamorphic rocks presently exposed at the surface were never less than 600m below the surface during the metamorphic episode (Barrow, 1893, p.352). Metamorphic intensity has been shown to increase from the south-east to the north-west, culminating around the study area. Barrow studied the minerals contained in the rocks and upon the basis of certain index minerals was able to delimit a series of zones, 'Barrow's Zones', which illustrate this trend. In Glen Muick there occur oligoclase-biotite-gneisses of the region of highest grade regional metamorphism in the Scottish Highlands. In these rocks Sillimanite is the metamorphic index mineral (Taylor, 1951).

Associated with the final stages of folding are the granite intrusions. Dykes of Newer Granite age are abundant in the area. They consist of a wide variety of compositions, colours and textures, but trend consistently north-east to south-west (Downie, 1954). The Devonian igneous rocks of Scotland are often distinguishable chemically from those of the Carboniferous and Tertiary periods. In general, the Devonian igneous rocks are almost wholly calc-alkaline in contrast to the Carboniferous and Tertiary rocks that are mainly alkaline. Some Tertiary igneous rocks approach a calc-alkaline composition but the occurrence of a soda-rich varieties best places them with the alkaline types (Bailey, 1958).

The crags around Loch Kander are formed in part by a small irregular mass of quartz-mica-diorite. A rounded mass of felsite gives rise to the crags in the valley of the Baddock Burn (Downie, 1954). A linear outcrop of felsite occurs to the east of the quartzite of the Cairnwell and several felsite outcrops appear to the south of this (Law, 1961). Local areas of contact metamorphism are associated with the igneous rocks and larger granite intrusions.

The granite masses are nearly circular intrusive bodies, the Lochnagar intrusion being almost 14 km in diameter. An annular arrangement of granitic rock types is displayed by the Lochnagar pluton. It was probably emplaced by means of caldera formation, intruded into a space created by down-faulting along ring shaped fractures of the crust (Mercy, 1965; Johnstone, 1966).

Altogether the Lochnagar granite occupies an outcrop area of about 155 km. The granite is remarkably constant in character and composition over its outcrop. It is a biotite granite of fine- or medium-grain, consisting of oligoclase, orthoclase, quartz and biotite (Barrow and Craig, 1912, p.84), and belongs to the later and more acid phase of the intrusive complex (Taylor, 1951).

Although the crystal size varies over the outcrop, no definite dividing lines can be drawn between the areas of fine- and medium-grained granites, the boundaries being gradations. Usually the rock is greyish in colour, tinged with pink by the alkali feldspars that are occasionally large and well developed. Biotite is a variable constituent, but the rock is never rich in biotite. Veins of more acid micro-granite and aplite are common, being usually vertical or steeply dipping. They are best seen in the faces of the corries. The veins often contain muscovite, and are rich in alkali feldspar with biotite as a rare constituent. Small intrusions of fine-grained granite, similar in character to the veins, occur throughout the mass but their outlines are hard to trace (Barrow and Craig, 1912).

The jointing system of the Lochnagar granite is regular and almost perfect, the usual three sets of joints, approximately at right angles, being seen in most of the cliff exposures. Two of the sets are vertical or very highly inclined. Small vertical faults and crush lines are frequent towards the southern boundary, nearly always coinciding with one of the systems of joints.

Towards the eastern margin of the intrusion, the granite is a coarse grained rock, with large pink porphyritic crystals of orthoclase, interstitial glassy quartz and some 10% biotite occuring as small flakes (Taylor, 1952, p.38). Considerable variations in both texture and grain size occur in the eastern margin. Marginal chilling is apparent, the rock becoming fine- to medium-grained, with a nearly equigranular texture of quartz, orthoclase and scarcer plagioclase, some areas producing a noticeably porphyritic type.

Xenolithic material, representing marginal stopping by the invading granite magma, is plentiful and correlates with the nearby country rocks.

Fresh granite from the Allt a' Chlaiginn stream section on the north side of Glen Callater, towards the south-western margin of the granite, is typical Lochnagar granite (Riddler, 1967, p.62). It is a medium-grained rock with a granular texture and smoky quartz (Cairngorm), dominant alkali feldspar, oligoclase and biotite. A porphyritic texture is evident, with a fine- to medium-grained groundmass, large pink crystals of alkali feldspar, biotite,hornblende and quartz.

Granite from the Glen Muick side of the intrusion is medium-grained with pinkish sub-idiomorphic orthoclase crystals, which stand out in relief on weathered surfaces (Taylor, 1951). The rock is generally leucocratic with almost 5% dark minerals. In thin-section orthoclase predominates among the feldspars, with occasional perthite and up to 15% quartz occurring mainly interstitially, and traces of oligoclase. The main ferromagnesian mineral is biotite.

The great granite mass of Kincardineshire, of which Mount Keen forms the north-west portion, is possibly a laccolith-like intrusion (Johnstone, 1966, p.50). As a whole the rock is typically granitic. The rock assumes a drusy character towards the western boundary, which is probably accompanied by a change in composition (Barrow and Craig, 1912, p.89). The cavities are lined with pyramidal crystals of quartz and more or less idiomorphic crystals of potash feldspar varying in size up to 5cm long, but usually smaller. Down Glen Tanar occur small veins with cavities at intervals. These veins cut the more normal granite. Crush-lines are numerous, and are often seen to be filled with vein or reef quartz. The granite of Mount Keen is very closely jointed (Bremner, 1912).

Intrusions of basic igneous rocks, also of Newer Granite age, occur around the margins of the granite intrusions. These outcrops cover a much smaller area. The most important outcrops occur at the head of Glen Clova, and around the eastern margins of the Lochnagar mass. Many of the basic intrusions are separated from the granite, but where they occur on its margin, a mixing of the two rocks is apparent (Barrow and Craig, 1912, p.73).

The Coyles of Muick at the mouth of Glen Muick are formed of serpentine (Bremner, 1912, p.80), emplaced along a large fault line (Barrow and Craig, 1912, p.74). At the head of Glen Clova, the Glen Doll complex, a basic intrusion composed of serpentine, picrite, basic diorite and diorite, lies across the greatest known fault in the district (Barrow and Craig, 1912, p.75; Bain, 1956). To the north of the Glen Doll complex there occur several diorite intrusions, the largest being the marginal diorite forming Craggan Hill, 2½ km to the east of Loch Muick (Taylor, 1951).

RELIEF AND DRAINAGE

3:2

To the north of the River Dee lie the Cairngorm Mountains, and to the south stretches the range of hills known as the Mounth, part of the larger Grampian Mountains. The Mounth range begins at the sea coast close to Aberdeen at Tullos Hill and rises westwards through Kerloch, Clachnaben, Mount Battock and Mount Keen (938m) to Lochnagar, or more correctly the White Mounth (McConnochie, 1891), the chief glory of Deeside (Ewen, 1950). Westwards from Lochnagar, the highest point of the area (1154m), the range is less definite through Glas Maol (1068m) and the Cairnwell (932m).

As a whole the study area is a denuded, gently sloping plateau between 600m and 900m, forming a portion of the great tableland of the south-eastern Highlands (Barrow and Craig, 1912, p.1). The platform rises slowly to the north-west, culminating in Beinn a' Bhuird at 1177m. Deep valleys dissect the uneven surface, the two masses of Lochnagar (1154m) and Mount Keen (938m) projecting above it. Remnants of the tableland are preserved in the granite of Lochnagar and also on the north-east side of Glen Clova.

The undulating plateau surface is dissected by intricate systems of shallow valleys 50-200m deep with gentle slopes. These valleys feed into the main drainage lines of the area that occupy the glacially deepened valleys. Where they enter the steep-sided glacial troughs, such as Glen Muick or Glen Clova, as hanging valleys, spectacular waterfalls and steep bouldery courses occur, carrying the waters for nearly 300m to the valley floors. A deep peat cover caps the plateau. The peat cover is broken by streams and eroded into 'hags' by wind and rain. Hags are outliers or islands of peat capped by moorland vegetation and separated by wide flats floored with dark peat, weathered granite fragments and sand.

The hills that rise above the plateau do so rather abruptly and present a contrasting surface, covered with thin peat and strewn with numerous boulders. This bouldery debris is often seen as continuous spreads in the form of screes or block fields, contorted and rearranged by gelifluction into block-fronted lobes and terraces, or as an uneven scatter of individual boulders. Hill summits are covered by summit blockfields or sheets of granitic sand and gravel surrounding isolated boulders. Peat is rare or absent on the high tops and only scattered clumps of summit heath vegetation can survive at the exposed sites.

The Dee valley is the main drainage line of the area. In contrast to most of the streams in the area, which flow south-west to north-east along the strike or transversely across the strike, the Dee valley runs almost west to east. Bremner (1912) described the Dee as the most important river to diverge from these directions, and explained its course as following the local deviations of strike caused by the intrusions of Newer Granite. Barrow and Craig (1912, p.5) described the river as one of the early eastward flowing consequents developed upon the original slope of country eastwards towards the North Sea. This view was modified by Linton (1951) who suggested that the drainage was established upon a once continuous cover of chalk raised directly from the floor of the Cretaceous sea and gently upwarped. Subsequent erosion has removed all traces of the chalk from the surface of Scotland.

The greater part of the course of the Dee is between two elongated granitic intrusions, the stream rarely cutting across granite rocks. Multiple river capture has greatly altered the stream pattern in the headwaters of the Dee, effectively shortening the stream (Bremner, 1912, p.p.12-16; Ewen, 1950, p.4).

GLACIATION

3:3

The landscape of the south-east Grampians was modified by successive glaciations during the Quaternary period, the newer features being in striking contrast to the older elements of the relief (Clapperton and Crofts, 1969).

Several widespread till sheets have been recognised in north-east Scotland, but interbedded interglacial deposits have yet to be discovered. Consequently several differing interpretations of the glacial history of the area have arisen. The most notable contributions were from Jamieson (1858, 1862, 1865, 1906), Bremner (1918) and Synge (1956, 1963). In essence these authors proposed two main phases of ice movement, one from the north-west and one from the south, followed by a readvance of the Dee glacier into the Aberdeen area. This interpretation differed considerably from the picture envisaged for Scotland by the first glacialist, Louis Agassiz (1840), of a major Scottish ice-sheet followed by a shorter period of valley glaciation. This view was firmly established by the writings of A. Geikie (1863) and J. Geikie (1894) who were able to obtain a general acceptance of the idea of a major Scottish ice-sheet, and a later period of valley and corrie glaciation.

The work of the Geological Survey (eg. Barrow and Craig, 1912) introduced a more complicated three stage sequence of ice-sheet, valley glaciation, then corrie glaciation. Charlesworth (1926) introduced the concept of a readvance of the ice-sheet when he identified the Lammermuir-Stranraer moraine. Simpson (1933) described a later Perth readvance based upon evidence from near the city of Perth, and a Loch Lomond readvance, recognised at the southern end of Loch Lomond and at Menteith in the Forth valley. A readvance to Aberdeen was described by Synge (1956), which he correlated with Simpson's Perth readvance, and a readvance to Dinnet, half way down the Dee valley, of Loch Lomond readvance age. These three readvance stages after the Main Ice sheet period were extended (Sissons, 1965, 1967) and accepted for several years. Recent work is now seriously questioning the validity of these concepts (eg. Paterson, 1974; Sissons 1974b, 1974c): only the Loch

Lomond readvance is now widely accepted. In the Aberdeen area Clapperton and Sugden (1972) and Murdoch (1975) have shown that the pattern of meltwater channels and associated fluvioglacial deposits is continuous across the supposed Aberdeen readvance limit. All the deposits were attributed by these authors to one phase of glaciation with ice from three sources co-existing in the Aberdeen area, and were considered to relate to the down-wasting of the last major ice-sheet. Farther up the Dee valley at Dinnet a similar situation exists. The supposed terminal and lateral moraines (Bremner, 1912, 1918, 1930; Charlesworth, 1955; Synge, 1956) have been reinterpreted as the fluvioglacial deposits and erosional features produced in association with a downwasting ice sheet (Clapperton and Sugden, 1972). Pollen analysis from Lochs Davan and Kinnord, two large kettle holes, revealed a complete stratigraphical sequence from Zone 1 - Zone V111 (Vasari and Vasari, 1968). A radio carbon date of 12,510 $\pm$ 310 B.P. was obtained from the core by Y. Vasari (Sugden and Clapperton, 1975). Thus it seems that deglaciation was completed relatively early in the late Devensian and ice did not occupy the Dee Valley as far downstream as Dinnet after about 12,500 B.P.. Consequently any evidence of post ice-sheet glaciation must be looked for farther up the valley.

Within the study area fresh glacial features are abundant in the corries and the upper sections of many of the valleys. These features have received little attention until recently. Only the works of Barrow and Craig (1912), Charlesworth (1955) and Synge (1956) having considered the glaciation of these hills.

Above the high level plateau of the south-east Grampians (600-900m) rise the summits of Mount Keen (938m) and the Lochnagar mass (1154m). Mount Keen holds a single corrie on its northern slopes; Lochnagar holds four, facing north to north-east. The major glacial trough of Glen Muick cuts into the plateau within the study area. It is these corries, the glacial trough and some of the other valley heads which contain clear evidence of the last glaciers (Sissons, 1972, 1975; Sissons and Grant, 1972).

All five corries contain fresh morainic features, either

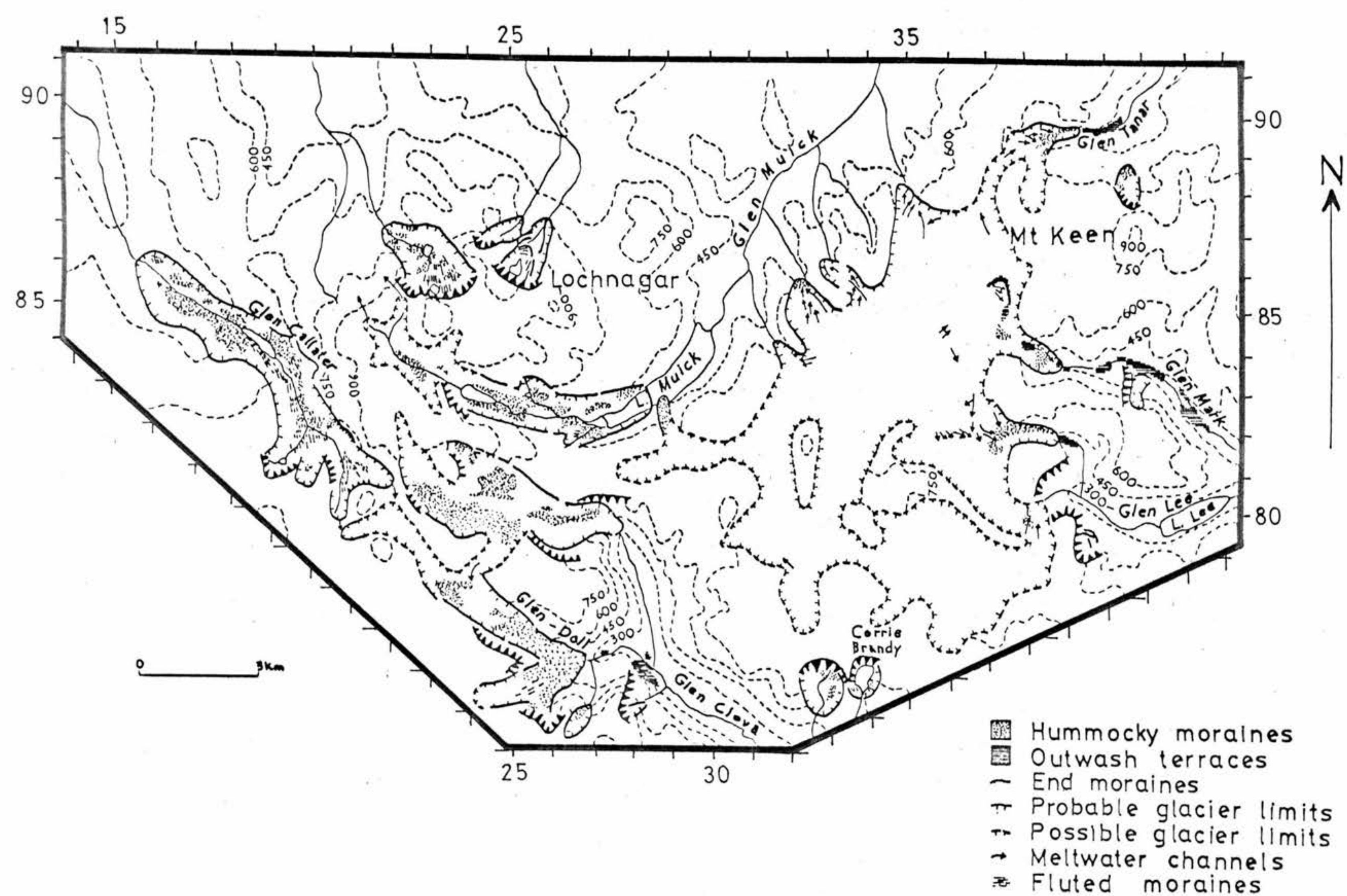


Figure 3.2 Limits of the Loch Lomond Readvance in part of the South-East Grampians (based on Sissons and Grant (1972) and Sissons (1972))

confined within definite lateral and terminal moraines, or showing a limited down-valley extent. The Mount Keen corrie exhibits a terminal boulder moraine about 1 km out from the corrie backwall. It is recognisable for about 800m. Inside the moraine the corrie floor and valley are covered with a dense litter of granite boulders, and towards the terminal moraine hummocky moraine features are abundant.

Of the four Lochnagar corrie glaciers, only the two eastern ones deposited identifiable bounding moraines. The large Lochnagar corrie is more than 1 km wide and nurtured a glacier that extended out to almost 2 km from the corrie backwall. A series of concentric boulder moraines is distinguishable upon the floor of the corrie, among an abundant cover of large granite boulders. These are recessional moraines, marking stages in the melting back of the glacier margin. Lateral moraines disturbed by gelifluction occur on the north-west slopes of the corrie. Coire na Cive, the shallow corrie adjacent to the large Lochnagar corrie, has a lateral boulder moraine several hundred metres long on its north-eastern margin. At its outer end the moraine begins to curve round before becoming indistinct. There are no boundary moraines to record the exact extent of the glaciers that were nourished, as one, by the two western corries. The two corries have almost merged by extensive erosion of the Stuic Buttress arête. Hummocky moraines occur upon the floor of the Stuic corrie and extend outwards in a zone that ends abruptly 2½ km from the corrie backwall. This limit of glacial deposits is taken to mark the maximum extent of the glacier, the limit coincides with a sharp decline in the number of large granite boulders that, as in the other three corries described, are abundant upon the floors of these corries.

The floor of Glen Muick is broken by a rock step, to the south of Loch Buidhe, which separates the valley into two distinctive sections. Above the rock step the valley has a wide and open form, containing the Dubh Loch. Below the step the Glen is a classic glacial trough with almost vertical walls in places, descending to the shores of Loch Muick. Fresh hummocky moraines occur in both valley sections especially around the Dubh Loch and at the head of Loch Muick. Large granite boulders are scattered over the valley floor. The lateral margins of the former valley glacier are clearly observable in places by a definite drift on the valley sides, well exposed in many of the steep and incised stream sections, and by long sections of lateral boulder moraines. Both lines of evidence show a marked decline in altitude downvalley. No terminal moraine is visible, but the glacier margin can be fixed at about 1½ km downvalley from the head of Loch Muick to which point a lateral boulder moraine on the northern slopes descends to the loch shore. No equivalent moraine is present on the southern slopes at the point, but the clear drift limits exhibit a similar decline to the adjacent shore.

Near the head of Glen Tanar there occurs an area of hummocky moraines and fluvioglacial features downvalley from a meltwater channel system. There is no terminal moraine. The decline in altitude of the features to the valley floor on the northern valley slopes indicates the glacier limits. At this point an outwash terrace begins. Whereas it can be envisaged that the deep but wide and open form of Upper Glen Muick would have been a suitable collecting ground for snow to nourish a valley glacier, the head of Glen Tanar appears most unsuitable. The valley ascends slowly to the plateau and its head reaches are in a shallow plateau valley. Similar conditions at the heads of Glens Mark and Lee, and other valleys radiating from the plateau to the south of the River Muick suggest that these valley glaciers were nourished by ice accumulating upon the plateau, possibly as a small plateau ice-cap (Sissons, 1972, p.177).

The corrie and valley glacier features described above are all relatively fresh forms situated in a landscape that shows evidence of fluvioglacial avtivity related to the decay of the major ice sheet. Such features occur on the south-east slopes of Cuidhe Crom (around no. 268855) where an ascending series of almost 30 sub-parallel meltwater channels cut into the hillside, and in the valley of the Lochnagar Burn (around no. 265885) where extensive fluvioglacial deposits are present. The age of the readvance can only be established at present by indirect evidence (Sissons, 1972; Sissons and Grant, 1972) No datable material has yet been found in the deposits of this area, and no pollen investigations carried out here. Comparisons of the form of the deposits of Loch Lomond age in the west of Scotland with those in the south-east Grampians reveal several similarities. The Loch Lomond readvance is the only one in Scotland that has been associated with definite terminal and lateral moraines, and that has fresh hummocky moraines within its limits. Fluted moraines have only been located in Scotland, on ground known or believed to have been covered by ice of the Loch Lomond Stadial. Finally, a further line of evidence is the relationship between the mapped glacier limits, and the distribution of large periglacial lobes.

Large periglacial lobes are a very obvious element of the periglacial landscape in this area. Major granite boulder lobes are well developed upon the hillslopes of Mount Keen and adjacent hills to the north. Similar lobes cover much of the high ground of the Lochnagar area, occurring on many hillslopes and over large areas of the valley sides above Loch Muick. Within the areas covered by the presumed Loch Lomond glaciers, these major lobes are absent. Only certain small scale features occur within the limits, such as gliding boulders, which are active today. Where boulder lobes occupy areas of slopes that descend into corries or the Glen Muick trough, they cease abruptly at the limits of the former glacier, even though the slope angles below the glacier margins are similar and boulders occur insufficient quantities to form lobes. Such conditions exist in the summit col above the Stuic Corrie (no 238859), above Loch Buidhe (no. 255834), above the Dubh Loch (no. 243817) and on the eastern ridge of the Mount Keen corrie (no. 411876). These relationships imply that major boulder lobes have not been formed since the moraines were deposited, and also that the valley and corrie glaciers were contemporaneous.

The evidence available at present strongly suggests that the corrie and valley glaciers developed during the Loch Lomond Stadial by a build up of glacier ice in favourable locations consequent upon a lowering of the snow line following a period of complete deglaciation (Sissons, 1972, 1974a, 1974b, 1974c, 1975; Sissons and Grant, 1972). Pollen analyses, radio carbon dates and other techniques used in the Great Glen and the North West Highlands by Pennington et al. (1972) yielded results that led them to suggest that the ice-sheet had disappeared from the North-West and the Great Glen by around 13,000 B.P.. Studies of beetle remains from deposits outside Scotland have revealed that by about 13,000 B.P. an intensely cold climate had been superseded by a climate with summer temperatures at least as warm as those of today (Coope and Brophy, 1972). The ice of the Loch Lomond Stadial did not begin to accumulate until about 12,000 B.P., so it seems likely that any vestiges of ice left in Scotland would have completely disappeared before the final stadial.

A different interpretation has been given for the Western Cairngorms by Sugden (1970b). He argued that no valley glacier phase occurred in that area, only a minor fluctuation of an ice-sheet, which had remained throughout the Lateglacial Interstadial, interrupting the overall decline of the ice-sheet. These contrasting interpretations of the evidence from adjacent areas have given rise to vigorous discussions in the literature concerning the Late-Glacial sequence of events (Sissons, 1972, 1973, 1974a, 1974b, 1974c, 1975; Sissons and Grant, 1972; Sissons et al., 1973; Sissons and Walker, 1974; Sugden, 1973a, 1973b, 1973c, 1974; Sugden and Clapperton, 1975; Clapperton et al., 1975).

These problems are considered in detail in the present study when the results of the investigations of the large boulder lobes, and the significance of their distributions are examined.

CLIMATE

3.4

Very little detailed climatic information is available for the hills of the study area..The only long term meteorological records are from the Braemar and Balmoral stations, both in valley situations. Thus the limited data from the valley stations can only be used to give a very general climatic picture of the hills. Weather in the mountains is different not in kind, but in the frequency and intensity of individual events (Pedgley, 1967, p.266).

The hills of the area have a severe climate (Mather, 1969; Summers, 1972, p.4). They experience great extremes of temperature combined with a relatively low rainfall. Within the study area occur some of the coldest frost pockets in Britain, namely Braemar, Glenshee and Balmoral. The lowest documented temperature for the area is from Braemar at 335m a.s.l.. In February, 1894 a temperature of -27°C was recorded.

Winter conditions in this area can be extreme with blizzards of arctic intensity lasting for several days (Fyffe, 1971, p.15), and winter temperatures that may sink to levels not normally associated with the British Isles (Smith, 1962).

Air Temperatures

Incomplete data from the Cairngorms meteorological station at 1091m led Summers (1972) to suggest that the mean monthly temperatures allowing plant growth to occur (5.6° C) prevail only from June to September. The equivalent figures from November to April rarely exceed 0°C. The mean annual temperatures at the White Lady Shieling in the Cairngorms for 1964, the only complete twelve months of records, was 4.7°C at (750m) and at the top of the ski chair lift was 2.3°C (at 1090m).

Temperatures for the period June to August 1970 were recorded at the top of the Cairnwell, in Glenshee, by Summers (1972, p.84).

Site	Elevation in metres	Temperature in ^{o}C mean max.	mean min	Mean	Growing season days
66	900	17.0	5.0	11.5	132
67	870	22.0	5.0	13.5	134
68	850	21.0	5.5	13.0	137

July is the warmest month in the study area. No mean monthly extremes for the summer period reach 25°C, although daily values of 25°C and above are occasionally recorded. (Mather, 1969). Temperatures of up to 27°C are recorded in the valleys in summer anticyclonic conditions (Alexander, 1968. p.27).

During the winter season ground frost incidence, from December to March, is one of the few constants, but this is on the valley floor rather than the warmer valley sides (Mather, 1969). The January mean temperature for the valley floors is only slightly above 0°C.

Mean monthly temperatures figures for the months October to April for the Braemar station are given below. They cover the twenty years 1942/3 to April 1962 inclusive.

	Oct.	Nov.	Dec.	Jan.	Feb.	March.	April
max	10.8	6.7	4.7	3.7	4.3	6.7	9.9
min	4.1	0.8	-1.1	-2.4	-1.7	-0.6	1.4
mean	7.5	3.8	1.8	0.7	1.3	3.0	5.6

Temperatures in °C.

Prolonged frost is characteristic of the valleys. Continuous frost was recorded in Braemar during the particularly severe winter of 1947, from January 27th to February 24th, when the temperature reached 0.6°C. It then fell below 0°C again until March 2nd. 1947 (J.C.Donaldson, personal communication). Intense frosts are similarly characteristic of Glen Tanar. In February 1955, 22°C of frost were recorded in the valley (Ross, 1958).

Conditions change rapidly with increasing height. Weather instruments on Ben Macdhui at 1255m, about 915m above Braemar, recorded temperatures averaging 7°C lower than Braemar, and up to 8°C lower for any one month (Baird, 1957).

Loch Muick occasionally freezes over in winter, but this is not a regular feature. Higher altitude results in an extensive ice cover above 760m, which remains until late April or early May

(Light, 1967). Hence the corrie lochan of Lochnagar at 777m is usually frozen over for most of the winter. The Dubh Loch often freezes, but the ice breaks up under stormy conditions so preventing a continuous ice cover for several months as on the corrie lochan of Lochnagar.

Data from the Cairngorms (King, 1968) indicate that freeze-thaw oscillations could take place there at any time in the winter, especially at low altitudes. They are more likely, and most frequent in spring and autumn, Rapid and large fluctuations of temperature are a feature of the study area. At Braemar, on March, 6th, 1947, the temperature rose from $-20^{\circ}C$ to $+2^{\circ}C$, and on the 18th, January, 1963, it rose from $-22^{\circ}C$ to $+0.6^{\circ}C$ (J.C.Donaldson, pers.comm.).

Precipitation

The mean annual rainfall for the 1,340 km catchment of the Dee is about 1,060 mm. p.a. (Mclean, 1936). No rainfall stations are sited upon the mountains of the Dee catchment.

Precipitation data from the valley stations in the study area, and nearby stations in the Tay drainage area, are given below (from the British Rainfall Supplement 1961-1965).

	map ref.	ht in m	annual average 1916-1950
Clunie			
Braemar	NO 152914	338m	927mm
Braemar (Irrigation Farm)	NO 148921	323m	978mm
Dee			
Balmoral	NO 260947	283m	846mm
Muick			
Altnaguibhsaich	NO 298857	418m	1184mm
Inchnabobart	NO 310875	387m	1125mm
Birkhall Sawmill	NO 347938	235m	879mm
Dee			
Ballater (Irrigation Farm)	NO 380965	192m	871mm
Tanar			
Glen Tanar House	NO 474958	168m	950mm
Dee			
Aboyne	NO 542982	116m	765mm
Blackwater			
Glenshee Lodge	NO 133684	335m	1153mm

No summer month on Deeside has rainfall of more than 79mm. The average driest month is June. Rainfall from the mild moist Atlantic air carried by the prevailing south-westerly wind is half or less than the rainfall of the Atlantic seaboard. There is an inverse relation between the annual amounts in the Western Highlands and lowland Aberdeenshire, less than 240 km away (Barry and Chorley, 1968, p.221). Totals only reach 1,500mm on the higher ground of the Cairngorms (Alexander, 1968).

Winter precipitation in the study area is largely as sleet or snow from December to March. Snow can be anticipated in all months except June to September on the low ground, and snow can occur all year round on the high tops. Snow and sleet can occasionally fall on low ground in June and September, but snow does not lie (Mather, 1969).

The hills of the study area are very exposed to winds from the north around to the south-east, the main snow bearing winds; consequently the snowfall is high. Aberdeenshire has a greater snowfall than Skye on the western seabord (Alexander, 1968). Snow lies late after winters of heavy snowfall. Extensive snow patches remain nearly all the year in the sheltered corries, and usually survive until July (Photographs 5.1, 8.1, and 8.2).

The first snow usually falls in the Cairgorms in October, and lies on the high plateaux to a depth of several centimetres from October to May (King, 1968). Strong winds, predominantly from the west or south-west, redistribute the snow and build cornices over lee slopes. Snow patches remain on north-east-facing slopes where they are protected from the sun's rays (King, 1968, p.60). Snow lies for an average of 100 days p.a. on the Grampian Mountains (Barry and Chorley, 1968, p.221).

The incidence of thunder and hail is rare in the valleys, mean values being 3 and 1 p.a. respectively (Mather, 1969).

Sunshine Hours

Sunshine hours are long in the spring and early summer, from April until July. May has 5.37 hours and June 5.30 hours daily average. These values are 1½ hours less than equivalent values for south coast stations such as Bournemouth and Torquay. Deeside is dry but cloudy in summer (Mather, 1969).

Fog occurs on average only twice a year in the valleys (Mather, 1969, p.10), but mists cap the hills for long periods in the summer, especially in the Cairngorms (King, 1968, p.58). On the Cairngorm plateau only one day in five is clear of mist (Humble, 1967, p.287).

Wind

The incidence of gale force wind is low in the valleys, the mean value being only 2 p.a.. This is not typical of higher sites (Mather, 1969).

No detailed records of winds exist for the hills of the study area, but limited figures are available from other Scottish hills. Records over 13 years on the summit of Ben Nevis, 1884-1903, revealed an average of 26 gales a year with wind velocities exceeding 80 km/hour (Pearsall, 1950, p.31). Hill tops in the Cairngorms are often swept by winds of hurricane force (33m/second: 120 km/hour - Barry and Chorley, 1968, p.261), especially in winter (Alexander, 1968). The mean monthly velocity of winds at the top of the Cairngorm chair lift from 1st, May, 1966 to 28th. February, 1967 was 8.0m/second (29 km/hour), and a record gust of 69.1 m/second (248.8 km/hour) occurred in March, 1947 (King, 1968). Many large wind velocities are not recorded due to icing up of the anemometer cups. Wind records from the top of Ben Macdhui showed values double and sometimes treble what they were in the valleys (Baird, 1957).

Wind conditions on Lochnagar are extreme. On the plateau (1,000m +) there are on average 230 days per year when the wind is of gale force (Whole Gale on the Beaufort Scale ≡ 24.5 to 28.4m/second) or more (Light, 1967, p.18). Winds are predominantly from a westerly direction with fairly strong south and south-easterly winds.

VEGETATION AND SOILS

3.5

Forests are the natural vegetation of the valleys of the study area, growing on the glacial and fluvioglacial soils containing a high proportion of granite fragments (Mather, 1969). In the Cairngorms a natural (potential) tree-line of between 610m and 690m, varying with topography and local shelter, was determined by Pears (1968). The lower height is more characteristic because of severe wind exposure. Isolated stunted species of trees, mainly rowan, occur to over 900m, and evidence of tree roots in peat show that the tree-line was formerly higher during post-glacial times, reaching to 790m in the late-Boreal (Pears, 1968).

At the present day heathlands grow on areas of destroyed natural woodland up to 610m. Heathlands (the Dry Heather Moor of McVean and Ratcliffe, 1962) are semi-natural. The underlying soils are not usually strongly podsolised, are mildly acidic in reaction and have a fairly high nutrient status (Mather, 1969). Heather (Calluna vulgaris) dominates the heathland vegetation, an assemblage that has been maintained for at least the last 300 years (Kayll, 1966) by the practice of 'Muir Burn', which involves the cyclical burning every 10-12 years of strips of the heath as part of the grouse moor management policies of the sporting estates (Whittaker, 1961; Kayll, 1966; Miller and Miles, 1969; Game Conservancy/Nature Conservancy, 1970). In recent times it has become accepted that these heathlands are almost completely artificial (McVean and Ratcliffe, 1962, p.38). Heathlands are anthropogenic. When heather moor remains unburned it may develop into a Vaccineto-Callunetum resembling that of the pine and birch woods from which most of it was originally derived (McVean and Ratcliffe, 1962, p.31).

Above the heathlands in the altitudinal zonation of the vegetation, occurs a narrow zone of juniper scrub. In areas of higher base status the zone widens and increases in altitude (Mather, 1969).

The moorland zone begins at around 670m. This is an area of blanket bogs with heather cotton sedge and heather deer sedge on deep peat, up to 1-1.3m. Frequently occuring species include Crowberry (Empetrum spp.), Cloudberry (Rubus chamaemorus), purple grass moor (Molinia caerulea), and Blaeberry (Vaccinium myrtillus) (Mather,1969). The peat is often eroded or hagged, and is typical of the high plateau.

Peat is essentially an accumulation of partly decomposed plant remains which have been prevented from normal decay by excess moisture at the soil surface. This moisture prevents aerobic decomposition in which oxygen, and the action of bacteria which require oxygen, are necessary. Three broad sets of conditions give rise to peat accumulations (Fitzpatrick, 1964). Firstly, gently sloping and depression areas where water can accumulate in the soil form Topogenic, Basin or Soligenous peat. Secondly, peat accumulates under conditions of high humidity and rainfall, such as on mountain tops. This type of peat is due entirely to climatic conditions and is known as 'Climatic Peat' or 'Blanket Peat'. Thirdly, soil horizons may develop which impede the vertical movement of water to such an extent that the soil surface becomes wet enough for peat formation. This also forms blanket peat. Peat layers vary considerably in thickness from a few centimetres, up to ten metres or more, but are only considered 'true' peat by the Soil Survey of Great Britain if they exceed 40cm.

The bog types differ also in their flora. Below about 450m Trichophoreto-Eriophoretum is the most widespread vegetation type, covering large areas wherever badly drained ground is extensive at low levels, as on valley floors amd gently inclined valley sides (less than 10^{o}). Calluneto-Eriophoretum bogs occur on wet moors from around sea-level upwards. The high level counterpart of the Calluneto-Eriophoretum is the Empetreto-Eriophoretum high level blanket bog. It is extensive on some of the elevated table lands of the Cairngorm and Lochnagar massifs, not being found below 760m.

Finally occur the summit heaths. The Cairngorm mountains in Aberdeenshire, Inverness-shire and Banffshire, and the north-eastern spur of the Grampian Highlands, comprise one of the most extensive tracts of Alpine Tundra in the British Isles (Summers, 1972, p.4). This zone is characterised by an abundance of Crowberry (Empetrum spp.) and to a lesser extent Blaeberry (Vaccinium myrtillus) and

Whortleberry (Vaccinium uliginosum), the peat thinning out from lower levels. The vegetation distribution in this zone is a factor-complex of exposure, snow duration and soil moisture (Mather, 1969), plus altitude (Watt and Jones, 1948; Summers, 1972).

The lower limit of the summit heaths is the zone where, owing to shorter snow cover, Empetrum is unable to compete with Calluna, Molinia and Trichophorum, and the upper limit is the zone where exposure becomes too great for dwarf shrubs (Mather, 1969). Microtopography is a very important factor at this level, as evidenced by the interesting micro-zonation of vegetation upon gelifluction lobes (Mather, 1969: this has also been described from Arctic Canada by Price, 1972; and from north-east Greenland by Ugolini, 1966; and Raup, 1969). The most exposed areas are characterised by a low percentage of ground-cover and patches of Scottish rush (Juncus trifidus), sheep's fescue (Festuca ovina) and stiff sedge (Carex bigelowii)along with Rhacomitrium moss. The soils are rankers or hamada mountain tundra soils. Buried soil profiles occur under certain types of lobes and terraces due to contemporary gelifluction processes. More generally the soils lack true profile development and consist merely of sterile gravel between boulders. A deep regolith is often present with soil processes little developed.

Lochnagar exhibits areas of snow-bed vegetation (Polytrichum alpinum - Carex bigelowii). This is a rare association, confined to high elevations in a band extending from Ben Nevis in the West to Clova in the east, with a southerly outlier on Ben Lawers (McVean and Ratcliffe, 1962, p.72). The stands range in altitude from 610m in Clova and Ben Lawers to over 1,200m in the Cairngorms and Nevis area. They occur on level or gently sloping sites, with a preponderance of northerly and easterly exposures, as is characteristic of areas of late snow-lie. The stands are neither extensive nor particularly homogenous except on Lochnagar where they usually form a mosaic with Nardeta, Dicraneto-Caricetum bigelowii and chionophilous moss heaths around the margins of large snow fields. The association is not fully understood, some occurrences being associated with drainage channels of melt water and wet hollows, others with well-drained sites or even raised soil patches. Soils under these associations are podsolic, and gleying of all horizons is frequent. Below the plateau of Glas Maol similar associations are seen on steep slopes in shallow hollows which hold snow late.

Hummocks caused by frost action occur upon the 1060m plateau of Lochnagar and Glas Maol. These hummocks are produced in areas where there is little snow cover on the ground. They are comparatively rare in Scotland (McVean and Ratcliffe, 1962, p.73).

CHAPTER 4

Frost Action, Mass Wasting and Landform Classification

"The dominant factors in landscape evolution in the periglacial environment are frost action and mass wasting. Frost action is the chief process responsible for preparing bedrock for erosion, while mass wasting is the chief method of transport" (Price, 1972).

Frost Action

Frost action is "the weathering process caused by repeated cycles of freezing and thawing" (Howell, 1962, p.196). The term includes a number of related processes such as frost wedging, frost cracking, frost heaving, frost thrusting and needle-ice growth. These processes serve as primary weathering agents in the initial breakdown of rocks, as well as being important factors in mass wasting mechanisms.

Freeze-Thaw Cycles

Chambers (1966, p.79) arbitrarily defined a freeze-thaw cycle in the ground as "the fall of soil temperature below -0.5°C and its subsequent rise above $+0.5^{\circ}$C". The frequency of freeze-thaw cycles is an important control in the effectiveness of frost wedging and some other kinds of frost action. Intensity and duration of freezing and the nature of the materials are also critical.

Washburn (1969) deduced from observations in the Mesters Vig district of north-east Greenland that only the annual freeze-thaw cycle is effective below a few centimetres depth. Williams (1973) stated that at present in Britain frost seldom penetrates the ground to more than one metre depth. Fahey (1973) observed from instrumental work in the Colorado Front Range that the number of frost heave cycles diminishes sharply with depth. None was recorded at a depth of 20cm. Fahey suggested that their geomorphic effectiveness was limited to the upper 10cm of the soil.

Large discrepancies are possible between air and ground temperatures during the day as a result of insolation, especially on dark surfaces, and at night because of outgoing radiation. It is possible for the ground temperature to fall below 0°C at air temperatures above the freezing point, and vice versa (Chambers, 1966). These factors would promote a lack of correlation between freeze-thaw cycles in the air and in the ground, and so it is hazardous to attempt extrapolation of freeze-thaw records of air temperatures to ground situations. Fahey (1973) found that the number of daily freeze-thaw cycles based upon air temperature recordings could not be relied upon to accurately predict the number of frost heave events at the soil surface.

Accurate descriptions of freeze-thaw cycle patterns in the ground can only be made using continuously recording temperature indicators, or by regular reading of thermistors or thermocouples placed at the site of the investigation. Such methods were used for example by Andrews (1963), Annersten (1966), Oke and Hannell (1966), Hannell (1973), and Everett (1966) in Canada, Harris (1971) in Norway, King (1968) and Halstead (1974) in Scotland, and Chambers (1966) in the Antarctic.

Frost Wedging

Howell (1962, p.197) considered frost wedging to be synonymous with frost weathering, which he defined as "the mechanical disintegration of earth materials brought about by frost action".

Frost wedging is the prying apart action by ice upon freezing and is synonymous with frost splitting and congelifraction (Bryan, 1946). The disruptive force is a result of the 9 per cent volume expansion accompanying the freezing of water, and in porous material may be due to ice segregation and the directional growth of ice crystals (Taber, 1950).

Coarse, angular rock debris wasting from bedrock in cold climates indicates the importance of frost wedging. Rocks can be reduced ultimately to silt size by frost action (Hopkins and Sigafoos, 1951; Taber, 1953). The parent rock exerts a critical influence on the size of its products during disintegration. Frost wedging of debris from bedrock surfaces produces rubble in the form of mountain top detritus and boulder fields (Dahl, 1966a), and is considered by some authors to be capable of cutting erosion terraces or altiplanation terraces by contributing to the backwasting of low cliffs (Eakin, 1916; Guilcher, 1950; Te Punga, 1956; Waters, 1962, 1964, 1965; Demek, 1968; Czudek and Demek, 1971), and producing tors (Palmer and Radley, 1961; Palmer and Nielsen, 1962; Waters, 1962, 1964). Frost wedging is responsible for the weathering of cliffs and rock outcrops causing rockfalls (Rapp, 1960, 1962; Prior et al., 1971), and producing screes (Young, 1972, p.131).

Freeze-thaw cycles are a primary factor in frost wedging. As mentioned above, the number of shifts of the air temperatures through the freezing point are by no means synonymous with freeze-thaw cycles in the rock. The length and intensity of freeze-thaw cycles in the rock, as well as the number of cycles are probably important.

Thawing of snow or ice adjacent to dark rocks warmed by insolation at subfreezing air temperatures is a potent factor in frost wedging when meltwater seepe into joints and refreezes (Gardner, 1969; Washburn, 1969, p.36). Subfreezing temperatures exist below the thawed layer throughout the year in a permafrost environment, and so refreezing of meltwater in lower lying jointed bedrock or in cracks in unconsolidated material is not confined to the spring and autumn, or to freeze-thaw cycles induced by changes of surface temperature. In the Karkevagge Valley of Sweden, an area with a seasonally frozen subsoil, Rapp (1960) determined that the maximum effect of frost-wedging, gauged by the release of rock fragments, probably occurs in spring. This was shown by the frequency of rock falls, that occurred perhaps as much in response to thawing following the annual freezing as to short term freeze-thaw cycles.

Frost Cracking

A frost crack is "an opening in the soil produced by the development of an ice wedge" (Howell, 1962, p.196).

Frost cracking is traditionally attributed to thermal contraction. Cracks develop when tensional forces produced by the rapid cooling of frozen soil exceed the tensile strength of the soil. Cracking is instantaneous and sometimes audible (Leffingwell, 1915). Thermal contraction cracks tend to occur as polygonal networks with intersections that are either orthogonal or non-orthogonal depending upon the homogeneity of the soil (Lachenbruch, 1960, 1962).

The width of the thermal contraction crack depends upon the thermal coefficient of expansion of the frozen soil, the magnitude of the temperature decrease, and the distance separating the crack from its nearest neighbours. Washburn et al., (1963), reported contemporary frost cracks due to thermal contraction occurring on a golf course in New Hampshire, and opening to 0.5cm.

Frost cracks may also be due to downslope soil movement processes (Benedict, 1970a, p.90). They should be limited to areas of extending flow, if this is the mechanism responsible, and oriented at right angles to the direction of soil movement.

Dessication cracking is another possible cause (Benedict, 1970 a, p.91). It can occur during the autumn freeze when water in the unfrozen shallow subsoil is drawn upward to supply growing ice lenses at the freezing front. Cracks caused by dessication have been described from the Antarctic by Chambers (1967).

Finally, differential frost heave may cause cracks to develop. Frost heaving in the Colorado Front Range varies from less than 1 centimetre in dry sites to 30 or 40 cm in areas where the soil is saturated (Benedict, 1970b, pp. 188-189). Marked differences in the effectiveness of frost heaving were observed to occur within short horizontal distances. Cracks would be expected to develop parallel to the axes of maximum heave. This hypothesis satisfactorily explained the frost cracks observed by Benedict (1970a, pp. 92-93), on a turf banked lobe in the Colorado Front Range.

Essential conditions for the formation of ice wedges are the presence of permafrost and an average annual temperature below $-5^{\circ}C$. Ice wedges are characteristic of the arctic, sand and composite wedges of the Antarctic (Berg and Black, 1966). Spring contraction cracks may be filled with hoar frost, melt-water or sand. In summer horizontal compression is set up by re-expansion of the permafrost. The following winter the vein acts as a zone of weakness when the permafrost contracts. Ice wedges build up by increments, and each successive annual layer can be measured and some estimate of the age of the wedge achieved (Berg and Black, 1966). As the wedge thickens the soil is prevented from returning to its original position. Active ice wedges have been recorded of up to 6m wide in peat (Walker and Arnborg, 1963).

Fossil ice wedges are recognised as casts, with infillings of sediments from above. A number of processes can produce features resembling ice wedge casts, which are known as false ice wedges (Johnsson, 1959); hence care must be taken in interpreting ice wedge casts.

Frost cracking of rocks, as a weathering process, was discussed by Washburn (1969). Experimants to simulate the volume changes caused by variations in temperature have not disproved that these changes can fracture rocks (Martini, 1967), but there is still no agreement as to its efficacy. Stones on the surface in the Mesters Vig district (Washburn ,1969), split apart and exhibiting fresh fracture surfaces, could not certainly be ascribed by Washburn to such volume changes, or to the effects of frost wedging or salt wedging along planes of weakness, or even to dirt wedging along pre-existing cracks.

Frost Heaving

Frost heaving is "the lifting of a surface by the internal action of frost. It generally occurs after a thaw, when the soil is filled with water droplets and when a sudden drop of temperature below freezing changes the droplets into ice crystals, which involves expansion, and consequently causes an upward movement of the soil" (Howell, 1962, p.196).

The classic works on frost heaving were published by Taber (1929, 1930, 1943, 1953), who described the results of laboratory experiments and field work to investigate the processes he had observed occuring on roads in the United States (Taber, 1916, 1918). Taber determined that the pressure effects accompanying the freezing of soils are due to the growth of ice crystals and not, as was formerly believed, due solely to a change in volume of the contained water upon freezing. His experiments showed that pressure is developed in the direction of crystal growth, which is determined chiefly by the direction of cooling. Heaving is often greater than can be explained by expansion alone, and was found to be due to the segregation of water as it freezes, more water being drawn up to the freezing front by molecular cohesion.

According to Taber, the chief factors controlling segregation and excessive heaving are the size of the soil particle, the size and percentage of voids, the amount of water available, and the rate of cooling.

The size of the soil particles was found to be one of the most important factors controlling segregation of water during freezing, its influence being clearly distinguished in the experiments from the effects of the size and amount of pore spaces. Samples of clays underwent excessive heaving, but under the same conditions clean sands were little affected. Even when the sand was so fine that capillary rise occured in it to a height of 20cm or more, segregation and excessive heaving did not occur.

Size of the capillary spaces in the soil determine the height to which water may be lifted above the water table by surface tension, the height being inversely proportional to the diameter of the capillaries. The water content of the soil limits the amount of heaving that is possible. This includes water in the soils before freezing and that which can be drawn up from below the freezing front. Rate of cooling, if slow, favours the formation of segregated ice layers. A slow lowering of the freezing isotherm occurs most commonly close to the surface and near the lower limit of frost penetration (Taber, 1929, p.443).

The depth of freezing does not directly affect the amount of surface heaving, but it is a limiting factor. The depth to which freezing extends depends upon the minimum temperature reached, the length of the cold spell, the amount of heat present in the soil and soil cover, and the changes produced in the composition and thermal properties of the soil because of segregation during freezing (Taber, 1929, p.445).

Frost Thrusting.

Frost thrusting is " lateral soil movement resulting from freezing" (Howell, 1962, p.197).

Taber (1943, pp.1458-1459) believed that horizontal thrust due to expansion on freezing was minimal and the only thrust is in the direction of cooling, which is upwards. This is based on evidence that the direction of crystal growth and the resulting pressures are at right angles to the cooling surface. The situation in a heterogenous material may be different: the direction of ice-crystal growth might be random because of varying conductivities that would influence the orientation of cooling surfaces.

Yardley (1951) described frost-thrust blocks from the Northwest Territories of Canada. These were raised above the surface of the ground by frost thrusting. Lateral expansion occurred within the well-jointed and foliated rocks when the contained water froze. Stress relief was obtained by loose blocks being forced up above the surface. This theory is analogous to the compression theory proposed to account for the development of fault ridge structures (Hills, 1963, p.181) by high angle reverse faulting (p.194).

Strong lateral pressures while the ground was frozen, possibly while permafrost was present, are thought to have formed an indurated horizon in the soils of parts of Scotland (Fitzpatrick, 1956). These pressures can also give rise to the orientation of clay mineral grains, forming platy structures in the soil, and forming clay skins around larger particles (Fitzpatrick, 1956; Romans et al., 1966), although similar features can be produced by percolation and eluviation either in periglacial conditions (Ragg and Bibby, 1966), or in temperate conditions (Brewer and Haldane, 1957).

Frost heaving and frost thrusting are intimately related. They both give rise to vertical movements and are usually either dealt with together (Price, 1972), or the effects are considered as heaving, the two components being difficult to distinguish.

Needle Ice Growth

Needle ice is "a slender needle-like snow crystal usually composed of needle-like components lying parallel, with the length of the crystal being at least five times greater than the diameter" Howell, 1962, p.341).

Needle ice can develop in all mineral soils from coarse sands to clays, but silty soils offer optimum conditions for its formation (Everett, 1966, p.215). Crystals of needle ice can range in length from several millimetres to 6 or 7 cm, or possibly more. The crystals generally form in the initial stages of freeze-up just below the ground surface and grow perpendicular to it. (Troll, 1958). Needle crystals usually form in bundles or clusters, but solitary needles are not uncommon.

Several layers of needle ice often develop, separated by layers of mineral soil. The mineral soil separations are usually only a few millimetres thick and seldom have any considerable lateral extent. Disconnected soil fragments are commonly scattered through any layer, and it is also common to find 0.5 to 1.5cm of dry powdery mineral soil capping the pedestals of needle clusters (Everett, 1966). Hay (1936) noted raised carpets of gravel supported on needle ice in the Lake District of England, on Hellvellyn. Successive daily increments of needle ice crystals built up a 6cm thick composite layer of needle ice which included soil material. Troll (1958, p.25) reported growths of needle ice up to 40cm thick in the Hoch Taunus of Germany. When the ice crystal layer melts the space which it occupied often remains open, leaving the soil friable and 'puffy' (Soons, 1967).

Everett (1966) found that needle ice grows downwards. During observations of needle ice throughout its period of formation he never found the soil beneath it to be frozen, which indicated that the water source was in the soil below. Taber (1929, p.443) determined that needle ice develops at the surface of moist clayey soils when the temperature of the ground immediately below the surface remains above freezing, while the air temperature is below freezing. His experiments showed that needle ice crystals do not form when previously chilled soils are rapidly frozen during a sudden drop in temperature. Hay (1936) also found unfrozen ground directly below the needle ice layer.

According to Everett (1966), needle ice has a lower limit in soils, which varies considerably from area to area, of between 9 and 14cm. The lower limit is sharply defined. Below this limit ICE LENSES (SIRLOIN FREEZING) occur. This is a textural and/or structural change. Ice lens production depends upon the texture of the soil, as well as the rate of the freezing line penetration and the supply of moisture (Everett, 1966, p.217). As the soil becomes finer in texture the ice lenses become thinner and the frozen soil takes on a streaked or sirloin appearance. Thick ice lenses near the surface are about 1mm, and lower in the soil they are 1/10 to 1mm thick.

CHEMICAL WEATHERING

Little work has been done on processes of rock weathering, other than freeze-thaw action, in the periglacial zone (Embleton and King, 1968, p.452). Chemical weathering especially has received scant attention.

Polynov (1937, p.163) believed chemical weathering to be almost inactive at the very cold temperatures of the arctic. Price (1972, p.25) too believed that chemical weathering is relatively unimportant in the periglacial environment due to low temperatures and the absence of water, which is frozen for much of the year. This results in most of the debris being coarse and angular. In contrast to these views Caine (1974, p.729) suggested that in the Alpine periglacial environment chemical weathering rates may be similar to those due to frost weathering, but Retzer (1974) believed that advanced weathering of rocks does not take place in the alpine periglacial climate. Chemical weathering in alpine environments is slow, but important; it is considerably less than generally occurs in warmer, more humid areas.

Temperature is recognised as an exceedingly important variable in the weathering environment (Keller, 1957, p.69). The low temperatures of periglacial zones are not in themselves significant, but they slow down the rates of chemical reactions and result in the elimination of free water to take part in chemical reactions. Leopold <u>et al.</u>, (1964, p.111) suggested that there might be a threshold amount of water necessary for chemical weathering reactions, below which weathering does not occur, but they were unable to reach any conclusions.

Tricart (1970, p.102) described the predominance of mechanical over chemical processes of weathering in the periglacial zone and indicated that chemical action can be important only in certain limiting cases as, for example, under snow banks that produce abundant meltwater rich in carbon dioxide. Williams (1949) established this concept after examining the carbon dioxide content of air below snow drifts in the Snoqualmie Pass, Cascade Mountains, Washington. The optimum temperature for the absorption of oxygen and carbon dioxide by water is at around $0^{o}C$. Samples of air taken from below snow drifts were found to contain twice as much carbon dioxide as the free atmosphere, leading to the conclusion that chemical weathering was enhanced under snow banks. The efficacy of this process has still not been established, even in abnormal concentrations, unless the bedrock is calcareous (Embleton and King, 1968, p.547). Smith (1972) believed that in alpine environments of low latitudes the process could possibly be made more effective where snow overlies soil and vegetation as the system would be enriched in carbon dioxide produced by biogenic processes. The process was doubted in high latitude snowbanks that undergo less freeze and thaw action, and are composed of snow types that are usually less porous.

Data from the southern French Alps (Clement and Vaudour, 1967) suggested that water from melting snow in that environment is acidic, the most frequent pH values being about 5.4, but ranging between pH 4.4 to 7.0. New snow was most acidic, when fresh and powdery, the crusted and granular old snows being the least acidic. The results suggested that the chemical action of melt-water from snow patches might be more effective where snowfalls occur frequently ie. in cold oceanic climates, and in high mountains during rapid melting when long sections of slopes are cleared of snow.

The pH of rain ranges from 4 to 8 with an average value of approximately 6 in places where the air is not appreciably contaminated (Leopold, Wolman and Miller, 1964, p.102). Clement and Vadour (1967) measured low pH values for fine cold rain in the southern French Alps, all readings being less than pH 6.0. Hence the solvent action of rain was concluded to be quicker than that of a snow layer melting on the ground. Similar experiments from Devon Island, N.W.T. Canada (Cogley, 1972), a high latitude arctic environment, found rainwater to be more effective solvent in limestone terrain than old melting snow. Also the solute load during a rainstorm flood in a small limestone drainage basin, was found to be greater than the suspended load. It is known that pH decreases with rising temperature from $0^{o}C$, a phenomenon that would increase the solvent effect of meltwaters that are warmed on sunny slopes, and of rainwater in lapies and hollows (Clement and Vaudour,1967).

Rising temperatures also cause the rates of many chemical reactions to rise exponentially, a factor that would assist the above effect. An examination of the form and rate of the solution of limestone in the high latitude arctic environment of North-West Somerset Island, Arctic Canada (Smith, 1972), revealed that the solution weathering of limestone would amount to about 2mm. in 1000 years in that area.

Analyses of rocks that are undergoing weathering under peri-glacial conditions provide valuable information concerning modes of weathering. Clay minerals belonging to the kaolinite family have been found at and beneath the surface of rounded, dolerite corestones making up tors at Sandy Glacier, Wright Valley, and in the McMurdo 'oasis' of Southern Victoria Land, Antarctica; (Derbyshire, 1972). X-ray diffraction of disintegrated material from the surfaces of joint blocks discerned kaolinite, Halloy-site and perhaps sepiolite, products of chemical weathering, formed in this case from the ancilliary biotite. The feldspars were fresh throughout. It is apparent from these results that on these dry ridge sites chemical weathering must have been acting slowly and continuously since the last glaciation. Studies of concentrically exfoliating sandstone outcrops and boulders in Spitsbergen (Embleton and King, 1968), by mineral analyses of the rocks and their shells, proved successive chemical changes. Expansion resulting from hydration or oxidation of the component minerals was found to be a factor, but it was considered frost would become increasingly important once splitting had started. The apparent chemical weathering of a quartz diorite boulder in the McMurdo Sound area of Antarctica was attributed to the combined action of frost wedging and the alternate solution and recrystallisation of mirabilite; this left efflorescences and coatings of mirabilite (hydrated sodium sulphate), calcareous, ferruginous and silicic compounds upon the surfaces of the rock (Kelly and Zumberge, 1961). Salt weathering may be an important agent of rock weathering in the dry valleys of Antarctica creating the frequently observed cavernously weathered boulders (Wellman and Wilson, 1965). This process requires a supply of salts, dissolved from the rock or deposited by spray or dust, and protection from the wind and rain. Salt weathering could be considered a mechanical rather than a chemical process, similar to the growth of ice crystals in rocks (Ollier, 1969, p.12).

Most cold regions research has demonstrated that the hydrolitic action of water and associated chemical weathering are of only subordinate importance in arctic climates on sandstones, quartzites, clays, and calcareous shales, phyllites, dolerites and many other rock types (Ollier, 1969, p.112). In cold, arid climates even the silicate rocks are only slightly affected by chemical weathering. Soil moisture, even after snow melt, is never present in sufficient quantity to initiate effective levels of chemical weathering.

Biotic weathering is important in most regions of the world; Polynov (1937) did not accept that completely sterile weathering could occur. There is nothing unique or peculiar about the biologic processes in periglacial environments, but the abundance of plants and animals and their activities are less than in more temperate regions (Price, 1972, p.25). Smith (1972) believed that the lack of a close soil cover was a significant factor in accounting for the reduced rate of solution weathering in Arctic Canada. Algae, fungi and bacteria that occur in arctic regions are believed to participate in the weathering of minerals (Ollier, 1969).

In general it can be assumed from the limited evidence available that chemical weathering has a restricted role in cold regions. More studies are necessary before any general conclusions can be drawn about the importance of chemical weathering in the periglacial environment.

MASS WASTING.

Mass wasting is "the gravitative movement of rock debris downslope, without the aid of the flowing medium of transport such as air at ordinary pressure, water or glacier ice" (Longwell, Flint and Sanders, 1969, p.162).

The progress of these movements is so slow that their presence is often not realised and so the recognition of the importance of mass movements in the shaping of the landscape has developed more slowly than our understanding of the other geomorphic processes of running water, glaciers, wind and waves (Sharpe, 1938).

Classification of mass movement phenomena is difficult as they are not isolated processes, but are part of a continuous series grading from dry debris movement into flow and glacier transport, and any one type may involve elements of another (Sharpe, 1938).

Sharpe published the first comprehensive review of gravitative processes and he devised a scheme of classification which is the foundation of many later schemes. In his book, Sharpe pointed out (p.10) that most of the previously published classifications dealt primarily with landslides, and not all could be considered as inclusive classifications of mass movement phenomena. He proposed a system whereby the kind of movement and its relative rate are taken as primary bases, the relative water or ice content as a secondary factor, then thirdly the kind of material. The new classification was discussed by Sharpe as four main groups:

Slow Flowage.	rock-creep, talus-creep, soil-creep, rock-glacier creep, and solifluction.
Rapid Flowage.	earthflow, mudflow, debris avalanche.
Sliding.	slump, debris-slide, debris-fall, rock-slide, rockfall.
Subsidence.	sinking of the ground over mines, caves, etc.

A more recent classification by the Highway Research Board Landslide Committee (1958) was devised for engineering purposes. This considered the type of movement and type of material as major parameters.

Although many types of mass wasting occur in periglacial environments, some processes are particularly widespread and operate most effectively in these conditions. The most important processes are Frost Creep, Solifluction, Talus Creep and Rockfalls and Avalanching.

Frost Creep.

This process is "the ratchet-like downslope movement of particles as the result of frost heaving of the ground and subsequent settling upon thawing, the heaving being predominantly normal to the slope and the settling more nearly vertical" (Washburn, 1967, p.10).

Creep of weathered material downslope was first recognised by Thomson (1877: outcrop curvature, plant roots, wetting and drying), Keeping (1878: outcrop curvature, freeze-thaw, roots), Coppinger (1881: wetting and drying), Kerr (1881: freeze-thaw), and Davison (1888a: insolation, 1888b: insolation, rain and snow, 1889: a quantative study of freeze-thaw). Davison (1889) described the influence of frost action in causing creep by heaving particles at right angles to the slope and their near vertical collapse. Sharpe (1938) defined the term creep as "the slow downslope movement of superficial soil or rock debris, usually imperceptible except to observations of long duration". Frost controlled creeps were cited by Sharpe and regarded as comprising rock glacier creep and solifluction, but solifluction is now usually regarded as a distinct process (Washburn, 1967, p.10).

The heaving and settling of particles may extend through the entire thickness of the mantle affected by frost action. Heaving is proportional to the total thickness of segregated ice layers that form in the freezing soil,is favoured by saturated conditions and by slow, deep freezing, and is important only in soils that contain sufficient fine textured material to permit water to move upward to the base of the frozen layer (Benedict, 1970,B). Frost creep should be greater in a subpolar or even temperate climate than a high polar environment where there tend to be fewer freeze-thaw cycles, and the depth of thaw is shallow.

Solifluction.

Solifluction was first described by Andersson (1906), which he defined (pp.95-96) as follows: "this process, the slow flowing from higher to lower ground of masses of waste saturated with water (this may come from snow melting or rain), I propose to name solifluction (derived from solum, 'soil', and fluere, 'to flow')". Water may also come from the thawing of frozen ground (Taber, 1943, p.1458; Wright, 1961, p.941). Andersson's definition did not limit solifluction to cold climates (Sharpe, 1938, p.35; Washburn, 1967, p.11), but as the examples were from such regions, misconceptions have arisen over the climatic limitations of the term, and owing to insufficient data concerning the mechanisms, the process is not fully understood. Wrong and doubtful applications of the term have resulted (eg. Baird and Lewis, 1957).

The prerequisite condition for solifluction is the saturation with water of a surficial mass of loose material, which attains a plasticity and viscosity, and then yields to gravity. No climatic limitations are contained in the definition but subsequent usage (eg. Eakin, 1916, p.76) has caused it to be associated with cold climates. Terms have been devised that describe solifluction under periglacial conditions. These include congelifluction (Dylik, 1967), gelisolifluction, cryosolifluction, and congeliturbation (Bryan, 1946).

Washburn (1967) discussed the various uses of the term solifluction, and considered the use of two terms for solifluction in cold climates, gelifluction and congelifluction. He agreed that the term solifluction should not be limited to cold climate phenomena. Congelifluction is solifluction associated with permafrost, and gelifluction is solifluction associated with frozen ground. Owing to the difficulty of distinguishing between deposits and landforms due exclusively to the one process as opposed to the other (a problem discussed by Troll, 1958, pp.18-19) and the wider applicability of the term gelifluction, Washburn adopted the term gelifluction for future use.

Washburn (1967) was able to make a distinction between creep and solifluction in the Mesters Vig District of north-east Greenland, but Harris (1971) was unable to differentiate between the two processes in the field in Norway.

Dahl (1956) pointed out that solifluction has a marked influence on vegetation, and that once the interrelationships of vegetation and solifluction have been worked out, the vegetation may be used in recognising localities with active solifluction and in deciding the degree of activity (p.273). This technique was used by McVean and Ratcliffe (1962, pp.159-160).

Dahl (1956) distinguished between amorphous and structured solifluction in the Rondane district of Norway. Amorphous solifluction is, according to Dahl, invariably associated with localities with a snow cover in winter and a late snow in spring. Solifluction lobes are common. Movement mainly occurs in spring when the meltwater soaks the soil to a 'soupy' consistency (p.279), which together with the slope was thought by Dahl to explain the phenomenon. Winter frosts were not thought to be an important factor in amorphous solifluction, as localities with deep snow are not exposed to winter frosts. Buried humus layers and an absence of soil profile development are characteristic, as also is a puckered and broken crust of lichens.Amorphous solifluction was believed by McVean and Ratcliffe (1962, p.159) to be a local type in Scotland, associated principally with the largest snow fields of the Cairngorms, although the effects are frequently obscured by erosion and deposition caused by the abundant rain water and melt water.

Structured solifluction was divided by Dahl (1956, p.280) into two subtypes, associated with polygons or with stony earth circles. In general, structured solifluction occurs on exposed ground, unprotected from winter frosts, the extent of its development being dependent upon the number and intensity of freeze-thaw cycles. Spots of active solifluction occur down to 300m in the Cairngorms, but soil polygons, nets, stripes, hillside terraces, soil hummocks and ridges are widespread in the Scottish Highlands over 760m (McVean and Ratcliffe, 1962). If Dahl's generalisations are correct, structured solifluction would be expected to be of greater importance in continental arctic areas than in oceanic arctic areas. As amorphous solifluction depends upon an abundance of snow, this type would be expected in the oceanic arctic areas.

The quantity of literature dealing with the measurement of slope movement is small (Everett, 1966, p.181), especially from cold environments. Washburn (1967) recorded downslope movement rates of between 0.6cm a year in relatively dry sites, to 6.0cm a year in wetter sites of the Mesters Vig district. Mean annual movement rates varied from 0.9cm in areas subject to summer dessication, to 3.7cm in areas that remained saturated. Harris (1971) in Norway, detected movements of 6cm on a slope of 11°, during the spring and early summer, and 4cm on a 6°slope. Benedict (1970b), measuring mass movement in the Colorado Front Range, recorded maximum rates of downslope movement ranging from 0.4 to 4.3cm a year. Smith (1960) measured movements of up to 36cm in 6 days for marked stones on the surface of the ground in South Georgia. He found that movement ceased at a depth of about 25cm by using marker stakes driven into the ground on a 21°slope. Throughout seven snow free months marked stones moved an average distance of 47cm, 25cm stakes moved 1.0cm and 10cm stakes moved 2.5cm. Dutkiewicz (1961) found that movement occurred to depths of between 20 to 25cm in Spitsbergen. He measured stone lines on the surface, which moved up to 4 or 5cm in a year or not at all. Jahn (1967, p.214) also working in Spitsbergen, used lines of stakes on the lower clayey sections of slopes, with gradients of less than 10°, to calculate present rates of solifluction which he recorded as being of the order of 10 - 12cm a year.

Dahl (1956) in the Rondane district of Norway, used stakes driven 10cm into the soil as reference poles for measuring the movement by solifluction of relatively level vegetated ground which showed little surficial evidence of solifluction (p.273). He measured movements of from a few centimetres to 6cm over a period of seven years. Rapp (1962) used stakes and painted boulders as movement markers in the Karkevagge Valley. Results showed frost heave of from 1 to 2cm a year, with downslope movement of about 4 to 7cm a year. A maximum rate of 25 to 30cm was recorded in a solifluction lobe.

Andrews (1963) recognised four main periods in the annual cycle of soil movement. Working in Labrador-Ungava, he measured frost heave using a specially constructed apparatus. The results were plotted as 'isoheave' maps for 5 day periods, from October 15 to to November 10, the effective frost heave period.

The available detailed records of contemporary solifluction and frost creep activity indicate that these processes have a significant role in the mass transfer of debris. Rapp (1960) estimated that solifluction moves 20,000 ton-metres a year in the Karkevagge Valley of Sweden.

Talus Creep

This movement process affects scree and rubble slopes by a combination of expansive freeze-thaw of interstitial ice (true talus creep), and settling caused by the washing out of fines (Rapp, 1960; Gardner, 1969). Contributive processes include individual rolling and gliding (Rapp, 1962; Gardner, 1969) and small talus slides (Rapp, 1962; Gardner, 1969; Drewry, 1973). The fall of blocks from the free faces above often serves to move particles upon impact (Gardner, 1973; Gray, 1973).

Rapp (1960) estimated that a total annual talus creep of 5,000 ton-metres a year occurs in the Karkevagge Valley. Movements varied from 10cm a year at the top of the talus slope to nothing at the base (Rapp, 1962). An average movement of 4cm a year, throughout a 20cm layer was calculated.

Gardner (1973) recorded movements of indivual stones on talus slopes, in the Canadian Rocky Mountains, of up to 70.99m in one year. This was an exceptional movement, 10-20cm a year were most frequently recorded. The mean shift of particles from 5 talus slopes varied between 6-111 centimetres a year from individual transects.

Avalanching and Rockfalls

Avalanching is the sudden and very rapid movement of snow and/or rock debris down a slope. The term has been widely applied to free fall, sliding and flow phenomena (Washburn, 1973). A key characteristic is rapidity of movement.

Three broad categories of avalanche exist: snow avalanches, rock avalanches, and mixed or snow-rock avalanches. They can occur anywhere, but are essentially a highland phenomenon, characteristic of steep slopes.

Avalanches in snow are classified as surface avalanches, ground avalanches and windborne powder avalanches. They can be wet or dry (Allix, 1924). Slab avalanches are dry, involving the release of a wind packed layer of snow and can be ground or surface avalanches.

Some avalanches can travel over distances of up to several miles (eg. Crandell and Fahnestock, 1965; Kent, 1966), and reach speeds of up to 140km per hour. The unusually long distance of travel of some avalanches is attributed to a cushion of compressed air at their base, which buoys them up and reduces friction, a process known as fluidisation. Such avalanches may descend many hundreds of metres in altitude, and even ascend obstacles. Such a mechanism is discounted for some examples (eg. Watson and Wright, 1969), lubrication may be a result of the nature of the bedrock.

Fraser (1966) and Atwater (1968) described many examples of large avalanches reported from all over the world, but they were mainly concerned with the Alps and the Americas respectively.

Avalanches are usually less spectacular than the catastrophic examples described. They are capable of descending to the valley floor and travelling up the opposite valley side, but more frequently deposit their load at the foot of the slope on which they originate.

In the Savoy Valley of the French Alps between 1908 and 1912, 43,430 cubic metres of material was deposited by avalanches, and between 1909 and 1910, 23,079 cubic metres was deposited (Allix, 1924). Ground avalanches were thought to have contributed 79% of this, and glacier avalanches 18%. Rapp (1960) estimated that avalanches transfer 5-10 cubic metres of debris a year in the Karkevagge Valley.

The term rockfall designates "abrupt movement of loosened blocks or beds of solid rocks detached from rock walls or the roofs of caves. Free fall is the main mode of movement, The group includes slope movements of widely differing dimensions, ranging from the breaking-off and falling of isolated stones, up to the fall of enormous rock complexes" (Zaruba and Mencl, 1969, p.88).

Rockfalls originate by the influence of gravity, jointing and tectonic fracture of the rock, weather effects, wedging effects of freezing water in joints, hydrostatic pressure, and a trigger mechanism such as under-cutting of the slope, earthquake or thawing. Avalanches occur upon steep slopes; rockfalls are usually confined to cliffs and free faces, and contribute to the retreat of cliffs. Rockfalls are the main process of addition to screes (Young, 1972, p.131).

Rockfall incidence has been correlated with freeze-thaw cycles in Ireland at the present day (Prior et al., 1971, p.136). Release of rockfalls was ascribed by Rapp (1960) to frost bursting, heavy rain, earthquakes, chemical weathering, snow block falls, ice falls, creep, thermal changes and wind. They were correlated with thawing after frost bursting (Rapp, 1960), with a frequency maximum in spring. Rapp (1962) recorded 25 cubic metres of debris falling from one rock wall segment in the Karkevagge Valley in 9 years, which he estimated would be about 250 cubic metres for the whole length of the rockwall.

Landform Classification

Frost Creep and Gelifluction Deposits

Frost creep and gelifluction deposits are found on gradients as low as 2^{o}. A classification of the resulting features should avoid the use of genetic names that stress the importance of one process at the expense of another (Benedict, 1970b, p.170), as the processes concerned are rarely separable and in most cases two are involved (Ball and Goodier, 1970, p.195). Most landforms produced by periglacial mass movement are polygenetic, the mechanisms involved varying through time, and the intensity of the processes differing as the climate changed, perhaps several periods of cold conditions having contributed to their formation.

Following the principles of Washburn (1956) a descriptive terminology based upon topographic form is outlined. This is the most satisfactory approach to a systematic description of landforms when the foundations of a genetic classification are in doubt (Ball and Goodier, 1970, p.195; Benedict, 1970b, p.170; Anderson, 1972, p.17).

Washburn (1973) classified the topographic form of frost creep and gelifluction deposits as follows:

1. Gelifluction sheets. Exhibit a smooth surface with a bench like or lobate lower margin.
2. Gelifluction benches. Have a pronounced terrace form, with the largest dimension paralleling the contour of the slope, making an angle of up to 45^{o} with the direction of the contour.

3. Gelifluction lobes. These features have a tongue-like appearance, with the longest dimension at right angles to the contour.
4. Gelifluction streams. Features with a pronounced linear form extending at right angles to the contour.

A second parameter that is often considered is the presence or absence of sorting (Washburn, 1956; Dutkiewicz, 1967; Benedict, 1970b). These terms are synonymous with 'stone-banked' and 'turf-banked' respectively (Benedict, 1970b, p.171). King, (1968, 1972), differentiated between 'stone-banked' and 'vegetation-covered' lobes, by the presence or absence of a stone garland. Demek (1969) distinguished between 'free solifluction' and 'bound solifluction', the latter being characterised by a restraining cover of turf.

Turf-Banked Terraces

Turf-banked terraces (Lundqvist, 1949; Galloway, 1961; Embleton and King, 1968; Benedict, 1970b), are "bench-like accumulations of moving soil that lack conspicuous sorting".

Alternative terms include 'solifluction terraces' (Rapp and Rudberg, 1960; Rudberg, 1962; Crampton and Taylor, 1967), 'benches' (Everett, 1966), "Turf-banked benches' (Ugolini, 1966), 'garland terraces' (Tufnell, 1969), 'soliflual garland terraces' (Jahn, 1958), and 'valleyside congelifluction terraces' (Ball and Goodier, 1970).

No features that can certainly be identified as turf-banked terraces were found in the study area. Terrace-like features with vegetated risers were examined, but these consisted of a boulder riser below a thin and irregular peat cover.

Turf-Banked Lobes

Turf-banked lobes (Galloway, 1961; Embleton and King, 1968; Ball and Goodier, 1970; Benedict, 1970b; Sugden, 1970) are "lobate accumulations of moving soil that lack conspicuous sorting".

They have also been called wavelike terraces and 'mammillary lobes' (Capps, 1919), 'soil tongues' (Williams, 1959), 'solifluction tongues' (Rapp and Rudberg, 1960; Rudberg, 1962), 'solifluction lobes' (Rapp, 1960, 1962; Rudberg, 1964), 'nonsorted congelifluction lobes' (Dutkiewicz, 1961,'gelifluction lobes' (Washburn, 1967), and 'vegetation covered lobes' (Galloway, 1958).

Lobes were examined in the study area which had vegetated risers, but as in the case of terraces, no restraining turf layer was in evidence, as a result of the coarse and rubbly nature of the material of the lobes. The lobes had an irregular peat cover over the surface of the lobe and over the riser, and so were strictly vegetation covered lobes (King, 1968, 1972; Sugden, 1970).

Stone-Banked Terraces

Stone-banked terraces (Lundqvist, 1949; Galloway, 1961; Benedict, 1966, 1970b; Embleton and King, 1968; King, 1968; Sugden, 1970, 1971), are "terrace or garland-like accumulations of stones and boulders, overlying a relatively stone-free moving subsoil".

Such features have been termed 'block-banked terraces' (Thompson, 1961), and 'solifluction terraces' (Sekyra, 1969).

Although limited in their occurrence and distribution within the study area, stone banked terraces were well developed on the granite rocks. Very few examples were found on the small area of metamorphic rocks examined and these in no way compared with the great lateral extent of those described from other parts of Scotland (White and Mottershead, 1972). Detailed investigations of a small sample of granite 'stone-banked' terraces was carried out.

Stone-Banked Lobes

Stone-banked lobes (Galloway, 1961; Embleton and King, 1968; King, 1968, 1972; Goodier and Ball, 1969; Ball and Goodier, 1970; Benedict, 1970b; Sugden, 1970, 1971), are "lobate masses of rocky debris underlain by relatively stone-free, fine-textured, moving soil".

Other names are stone garland's (Sharp, 1942), 'stone-banked tongues' (Rudberg, 1962), 'sorted congelifluction lobes' (Dutkiewicz, 1961), stone fronted lobes (Galloway, 1958), and lobe-like congelifluction structure (Dylik, 1969).

'Stone-banked' lobes were the most frequently developed feature on the granite and metamorphic rocks of the study area. The close spacing of several lobe series (King, 1972, p.154), indicated that snow avalanches from the cliffs above the talus down the flanks of many of the hills, give the profiles a stepped appearance. Lobes on the granite rocks were examined in considerable detail. A large sample were investigated from both the Mount Keen and Lochnagar massifs, and comparisons made with a small sample of lobes studied in the Glas Maol area, developed upon metamorphic rocks.

Block Fields and Block Slopes

Block-fields and block-slopes develop upon mountain summits and the higher flanks. They have a pattern of surface orientation in which the material tends to be aligned parallel to the local slope direction, and in which the strength of this alignment increases with downslope distance (Caine, 1972; Washburn, 1973). A secondary mode directed across the slope is often detectable that reaches a maximum near the edge of the field where the movement slows or ceases.

The exact origin and significance of block fields is still very much in doubt (eg. Dahl, 1966a, 1966b; Ives, 1966). It is generally agreed that they are of periglacial origin, confirmed by the block fabrics. Whether the block fields are developed entirely *in situ* by the frost weathering of the hill summits,or some or all of the constituent blocks are of a derived nature, is not known. The period of formation and details of the mechanisms are still in question (Washburn, 1973).

Extensive sheets of block rubble cover the hills in the study area. For the most part the blocks are covered by a thin layer of vegetated peat, or submerged in a sandy matrix that supports a sparse vegetation. In places wind erosion has formed small crescentic erosion scars in the sandy debris of the summits (King, 1971b). The hillslope debris is usually reformed into lobe or terrace features, but the crest slopes and certain slope sections exhibit block slope features of undifferentiated block spreads, which gradually give way to lobes and terraces.

Gliding Boulders

Gliding boulders are isolated stones, usually of boulder size, that move downslope faster than the surrounding material. They are recognised by the elongate depression left upslope, created by the passage of the block, and a low ridge or turf roll ('bow-wave') downslope that the moving block pushes up ahead of itself.

Gliding boulders have received very little attention in the British Isles (Tufnell, 1972). They have been recognised by a number of authors (Hollingworth, 1934; Hay, 1937, 1942; Galloway, 1958, 1961b; Tivy, 1962; Rudberg, 1962; Smith, 1962; Lyford et al., 1963; Sissons, 1965; Ragg and Bibby, 1966; King, 1968; Williams, 1968; Goodier and Ball, 1969; Sekyra, 1969; Tufnell, 1969, 1972; Ball and Goodier, 1970; Sugden, 1970a; Washburn, 1973; Fenton, 1974). The most detailed work is a comprehensive study by Tufnell (1972).

They have been variously referred to as 'Gliders' (Hay, 1937, 1942), 'Gliding Blocks' (Galloway, 1961b; Williams, 1968), 'Shifted blocks' (Sekyra, 1969), 'Gliding boulders' (King, 1968; Sugden, 1970a) and 'Ploughing blocks' (Tufnell, 1972; Washburn, 1973).

Large numbers of gliding boulders were examined in the study area. They are well developed both in the granite and metamorphic areas.

Avalanche and Rockfall Deposits

Dirty snow avalanches have a direct morphological influence if they are of the ground type (Rapp, 1960). They erode the slope and deposit avalanche boulder tongues at the foot of the slope (Rapp, 1959). Avalanche gullies are carved out in situations in which avalanches repeatedly occur (Allix, 1924), achieving erosion by a gouging and plucking action.

Snow avalanches have an indirect morphological role in that they are capable of dislodging rockfalls. Avalanches have a large transporting capacity and are effective in sweeping debris from both open slopes and gullies.

Rockfalls contribute to the build up of screes at the foot of rock walls (Rapp, 1960, 1962; Gardner, J.S.,1969; Gardner, J.,1970; Gray, 1973; Young, 1972). Cliff recession as a result of rockfalls modifies the shape of rockwalls in corries and glaciated valleys.

Luckman (1971) examined the effects of avalanches upon talus slopes in the Jasper Area of the Canadian Rockies. His results can be an important or even dominant mechanism in the development of talus slopes. They were observed to carry large amounts of debris onto the talus, and erode and deposit upon the surface of the talus slope. Luckman concluded that although rockfalls were perhaps dominant upon a global scale, snow and slush avalanches, and other forms of mass movement may become dominant locally.

Rapp (1959), described accumulations of rock debris deposited by avalanches in Lappland. He claimed that they had not been distinguished previously, and that they are able to give valuable information about the localisation, frequency and eroding capacity of snow avalanches.

Rock falls and avalanches produce talus-cones at the base of steep chutes. Avalanches deposit avalanche boulder tongues (Rapp, 1959), far out onto the flat ground of the valley.

Avalanche boulder tongues are of two types, road-bank tongues, which are upraised with a flat ridge-like top, and fan tongues, which are thinner, go further out onto the valley floor, and wider. Debris in these features is roughly size sorted with the larger boulders at the sides and front of the tongues. Lanes of destroyed timber often mark the avalanche tracks.

Small, straight ridges of debris may occur on the distal side of large fixed boulders, situated in avalance tracks (Rapp, 1959; Potter, 1969). These are known as avalanche debris tails, and may extend up to 5 or 10m from the boulders. They are thought to be deposited in the quiet lee of stones (Potter, 1969), very similar to sand shadows (Bagnold, 1941), or by erosion of the surrounding debris leaving the tail as an upstanding feature protected by the rock (Rapp, 1959). Gardner (1970, p.142) described debris tails which are common in the Lake Louis area of Alberta, Canada and concluded that the cases examined were erosional remnants.

Slush avalanching is an important erosive agent in arctic and alpine areas (Luckman, 1971; Gray, 1973; Washburn, 1973). Slush avalanches are particularly dynamic in the arctic zone in Spitsbergen, and have pronounced effects upon the landscape (Jahn, 1967). Slush avalanching is considered to be important in the Alpine Zone of New Zealand where it has been incorporated into a model for talus slope development by Caine (1969).

CHAPTER 5

BOULDER LOBES

Introduction

Hillslopes in the periglacial environment are commonly mantled by a thick veneer of debris, produced by mechanical weathering of the bedrock. Gravitative processes continually act upon this unconsolidated cover and may displace it more or less uniformly as a sheet or, more commonly, as discrete lobate streams and tongues separated by zones of slow or zero flow. This form of mass movement leads to the production of structures referred to in the literature as solifluction tongues or lobes, garland terraces, steps or stone-banked lobes.

Lobes are U-shaped in plan, having a convex front that faces downslope. The steep frontal slope is termed the riser, and may vary in height from below 1m, to 5m or more. Several lobes commonly occur side by side across a slope forming a series (King, 1972, p.154), their fronts usually paralleling the contours. Single lobes frequently encroach upon each other to produce a step-like slope. The upper surface of the lobe is known as the tread, which may or may not be distinguished from the riser by a more complete cover of vegetation.

Large boulder lobes are the most extensive and the most impressive periglacial features in the granite parts of the study area, and smaller rubble lobes are common in the quartzite area. The light-coloured boulder garlands give the hillslopes a distinctive appearance (Photographs 5.1 and 5.2) both in the field and upon aerial photographs, sometimes exhibiting a complex tracery of steep boulder walls.

Previous Work

Although gelifluction features, in the form of 'step-like terraces in plateau frost debris', had been identified by the Officers of the Geological Survey over sixty years ago (Peach et al., 1912, 1913; Crampton and Carruthers, 1914) about the time that similar features were being described from Alaska by the United States Geological Survey (eg. Eakin, 1916; Capps, 1919), such periglacial mass movements features received relatively

PHOTOGRAPH 5.1 View towards Cuidhe Crom illustrating the mantle of granite boulders upon the south-east slopes, and their arrangement as crescent-shaped risers.

PHOTOGRAPH 5.2 The abrupt downslope termination, at the lateral limits of the Stuic Corrie glacier, of lobes in the summit col.

little further attention in this country until the work of Galloway (1958) and King (1968).

The few isolated mentions of lobes or terraces usually referred to them descriptively. Thus Hollingworth (1934), describing solifluction phenomena in the northern part of the Lake District, wrote about terraced debris and related forms, and "more or less horizontal spreads of angular debris - with a steep, advancing, semi-circular front" (p.175). He also mentioned terraced features on partially turfed areas and the steep turfed bank of the lobe-shaped downslope termination of screes. Hay (1937) recognised terraces with a vegetated lower boundary, a 10 to 15cm high riser and a gravelly surface (tread) upon the summit areas of the Ullswater district. He also noted the tongue-shaped lower boundary of soliflucted screes. Later, Hay (1942, p. 168) referred to garlands or "waves of loose matter descending the slope under solifluction", which were presumably small debris lobes or irregular terraces.

'Terraces' occurring in the Cairngorms were described by Watt and Jones (1948). The features were formed of muds, the frost-shattered rubble of the higher ground, the moraine of the valley margins and valley floors, and of massive boulders. References to the "curvature of the retaining bank" and the "terraces - arranged topographically side by side and one above the other" suggests that the authors were in part describing vegetation-covered, mud and boulder lobes. Boulder terraces in the Cairngorms were definitely identified by Metcalfe (1950). He also described a distinct form of 'oval terrace' with a crescent-shaped bank and roughly oval platform (tread), occurring side by side on 15°-20° hillsides. These features are undoubtedly what are now termed lobes. Terraces were also identified on the Isle of Arran (Watt and Jones, 1948) and on Unst, one of the Shetland Islands (Spence, 1957).

Te Punga (1957) recognised 'block-scallops' below tors on Bodmin Moor. They were said to occur as "several series of concentric scallops - - best developed some distance from the parent tor". Individual scallops, it was suggested, were solifluction lobes.

The first comprehensive descriptions of lobes and terraces occurring upon hills throughout Scotland were given by Galloway (1958). He identified stone-fronted and vegetation-covered lobes in many upland areas of Scotland, and also identified stone-banked terraces, turf-banked terraces and terracettes. Galloway gave some indications of the angles of slope upon which these features develop, and the widths (eg. 4-30m wide on Ben Wyvis p. 122) and heights (eg. fronts up to 6m high on the Lochnagar-Broad Cairn Massif (p.132) that some examples attained. The Lochnagar examples were termed stone-fronted lobes (Galloway, 1958, p.132). Later (1961a, 1961b) he used the term stone-banked lobes for similar features.

In a review of the periglacial geomorphology of Scotland Fitzpatrick (1958) described contemporary debris terraces upon mountain slopes but failed to recognise the huge fossil features.

Large 'solifluction terraces' up to 2m high and 10m broad were later identified upon the island of Rhum on Ruinsival (Clark, 1962). These features were believed to be fossil, but smaller currently active terraces were found at many localities throughout southern Rhum. Currently active 'frost terraces' of small stones, developed upon the Hallival-Barkeval ridge on Rhum, were recorded as moving during the winter of 1963 (Eggeling, 1964). Terracettes, 'miniature turf-bound lobes' and 'lobe-like terraces' were observed upon slopes over 20^{o} in the Lowther Hills by Tivy (1962). Ragg and Bibby (1966), also working in the Southern Uplands of Scotland, described patterns of solifluction lobes upon the highest summits. They referred to the lobe-risers as "the steeper downslope edges" (p.21).

'Rubble-drift terraces', flanking moorland streams in south-west England, were described by Waters (1965). They were built of 'main head' from the valley sides. Although they were gently sloping Waters particularly noted that they were not related to the gradient of the stream. Similar features were identified in some upland valleys of south and central Wales by Crampton and Taylor (1967) and Watson (1961). Some of these 'solifluction terraces' had previously been mapped as river terraces (Crampton and Taylor, 1967, p.15).

A very detailed study by King (1968, 1972) described stone-banked, turf-banked and vegetation-covered lobes in the Western Cairngorms. The study included the results of investigations of lobe sizes, the angles of their facets, the nature of their structure and their boulder-size composition. Attempts were made to define the factors influencing the distribution of the lobes, particularly of the three different types.

The few studies of lobes that have appeared since King's (1968) work were largely concerned with noting the existence of such features in new localities. Very few details, similar to those presented by King (1968, 1972), have been published.

Goodier and Ball, (1969) described terracettes and stone-banked lobes occurring in the Rhinog Mountains of north Wales. They later (Ball and Goodier, 1970) published a more detailed study of periglacial features in Snowdonia that included an examination of the occurrence, general size and mode of origin of valley-side gelifluction terraces, stone-banked lobes, turf-banked lobes and terracettes. In mid-Wales, Potts (1971), recognised valley-side terraces, some of which were lobate.

Sugden (1970a, 1971) discussed the distribution, general size-range and the possible age of a variety of lobe and terrace forms occurring in the Cairngorm Mountains. Similarly, Kelletat (1970a, 1970b) presented general surveys of the distribution, relationships and peripd of formation of fossil and recent periglacial features in the Scottish Highlands. These studies paid particular attention to the solifluction forms described as lobate, garlanded and terraced features. Ryder and McCann (1971) identified and distinguished between large, relict terraces, on smaller, active solifluction terraces and lobes on the island of Rhum. White and Mottershead (1972) excavated the sides of a stream gully cut through a turf-banked terrace on the slopes of Ben Arkle, Sutherland. They produced a detailed contour map of the feature and carried out sampling of the vegetation, soils, stone orientations, particle size distributions and the nature and pollen content of a buried organic horizon. The buried organic layer reached a maximum thickness of 10cm, and extended back under the terrace for about 3m. Radio-carbon dating of the layer at this point gave an age of 5145 $\pm$ 135 B.P., indicating that the terrace had moved forward during the last 5,000 years.

Recently the distribution and age of large periglacial boulder lobes have been the subject of much debate in papers dealing with the deglaciation pattern and suggested corrie-glacier readvance phase in the Cairngorm Mountains and South-East Grampians (eg. Sissons and Grant, 1972; Sissons, 1972, 1974a, 1974b, 1974c, 1975; Sugden, 1973c, 1974; Sugden and Clapperton, 1975). Part of the confusion results from a general lack of knowledge of the nature and origin of the various periglacial lobe features.

The Present Study

Research in the present study was concentrated upon attempting to analyse, more fully than has been done to date, the distribution and characteristics of granite and metamorphic boulder lobes in a part of Scotland. Of particular concern was the size to which these features develop in different slope and terrain situations, and the distribution of the granite lobes in relation to the limits of the presumed Loch Lomond corrie glaciers.

Fourteen parameters were established to summarise the main characteristics of each lobe sampled, and the circumstances of its occurrence. The fourteen parameters are as follows:

Altitude: the approximate elevation above sea-level of the example.

Aspect: the orientation, with reference to magnetic north, of the slope segment upon which the example occurs.

Slope-Angle: the angle of declivity of the slope upon which the lobe is developed. This was a rather difficult quantity to measure as the slopes were often covered with descending lobe-series giving the slope a stepped long-profile; in this case the slope angle was measured tangentially to the crests of all lobe-risers occurring down the hillside (all angles measured by Abney level).

Surface-Angle: the angle of declivity of the lobe-tread. Usually the tread had a convex long-profile and so this reading had to be generalised. The reading was taken down the forward, steeper part of the tread, from the upslope end of the longer of the two lobe sides, down to the crest of the riser.

Angle Below: the angle of declivity of the slope-segment immediately in front of the lobe, beginning where the bouldery riser terminates. In many cases this slope was the upper section of the tread of a lower lobe.

Riser-Angle: the angle of declivity of the lobe-riser, measured at the centre of the lobe-front.

Lobe Spacing/ Length: the distance in metres, measured in a line directly up the slope from the riser-crest to either, the base of the riser of the next lobe upslope, or, to a point where the convexity of the lobe long-profile fades into a featureless slope.

Lobe Width: the distance,in metres, across the slope between the upslope terminations of the two lobe sides.

Riser Length: the distance in metres from the riser crest to the base of the riser. The latter point is usually characterised by an abrupt change in gradient to a shallower slope.

Right-Hand Length) Left-Hand Length): the distance in metres from the centre of the riser crest to the upslope termination of each of the two lobe sides. These measures were recorded in a line directly upslope from the centre of the curved downslope edge of the lobe tread, at the riser crest, while measuring the lobe spacing/length.

Lobe Thickness: the thickness of the debris layer forming the lobe was calculated in a direction normal to the slope upon which it was developed. The slope angle was taken to be angle-below which, it is assumed, was the slope-segment down which the lobe had last progressed: - The angle of the riser and the length of the riser are known. This measure indicates, approximately, the depth of the former slope-surface below the riser-crest.

Lithology: the type of rock of which the lobe-boulders are composed.

Vegetation: the nature of the slope and lobe vegetation and features of its distribution upon facets of the lobe.

Study Areas

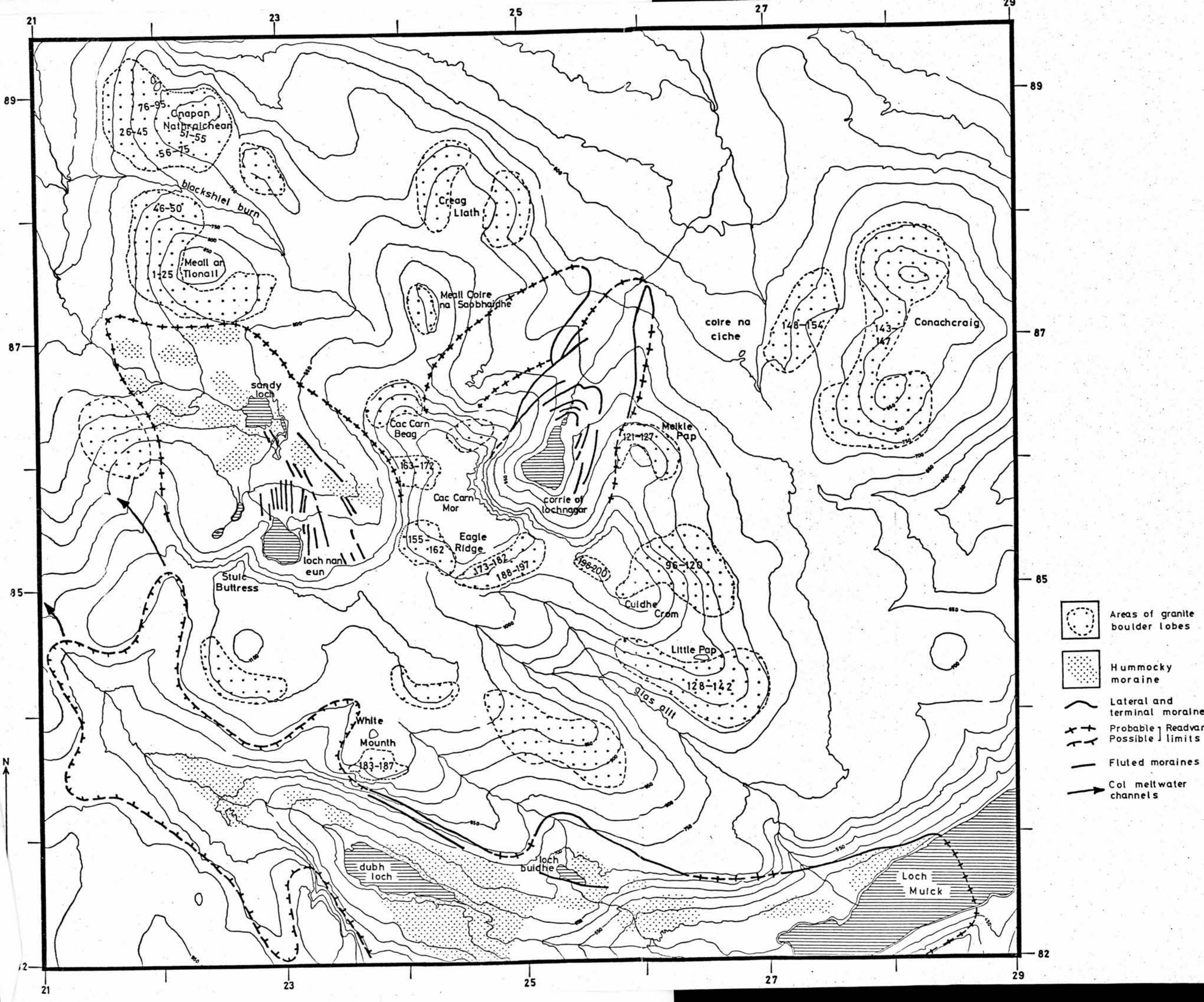
Aerial photographs indicate the very bouldery nature of the terrain in the study area. Large boulders, up to a metre or more long, litter the hillslopes and valley and corrie-floors in the granite areas. Boulders in the metamorphic area are smaller, usually less than half a metre long.

In both areas, upon aerial photographs and in the field, the bouldery-debris appears to form crenulated patterns upon the hillsides (Photographs 5.1 and 5.2), often in long wave-like lines, paralleling the slope contours, and arranged one above the other. These patterns are the fronts, or risers, of the boulder lobes. They usually appear light in colour against the dark vegetation of the slope surface and the lobe-treads.

Lobes were examined in detail from three areas within the granite and metamorphic terrains. One hundred granite lobes were sampled from the hillslopes of Gathering Cairn (map ref. NO 424885), Braid Cairn (NO 426873) and Mount Keen (NO 409869) of the Mount Keen granite mass. Two hundred granite lobes were samples from the flanks of the hills that surround the summit of Cac Carn Beag (NO 243862), together comprising the Lochnagar Massif. Finally, fifty quartzite lobes, in the metamorphic area, were sampled upon the flanks of hills to the north of the Glas Maol watershed, to both the west and the east of the Cairnwell Burn (NO 145789).

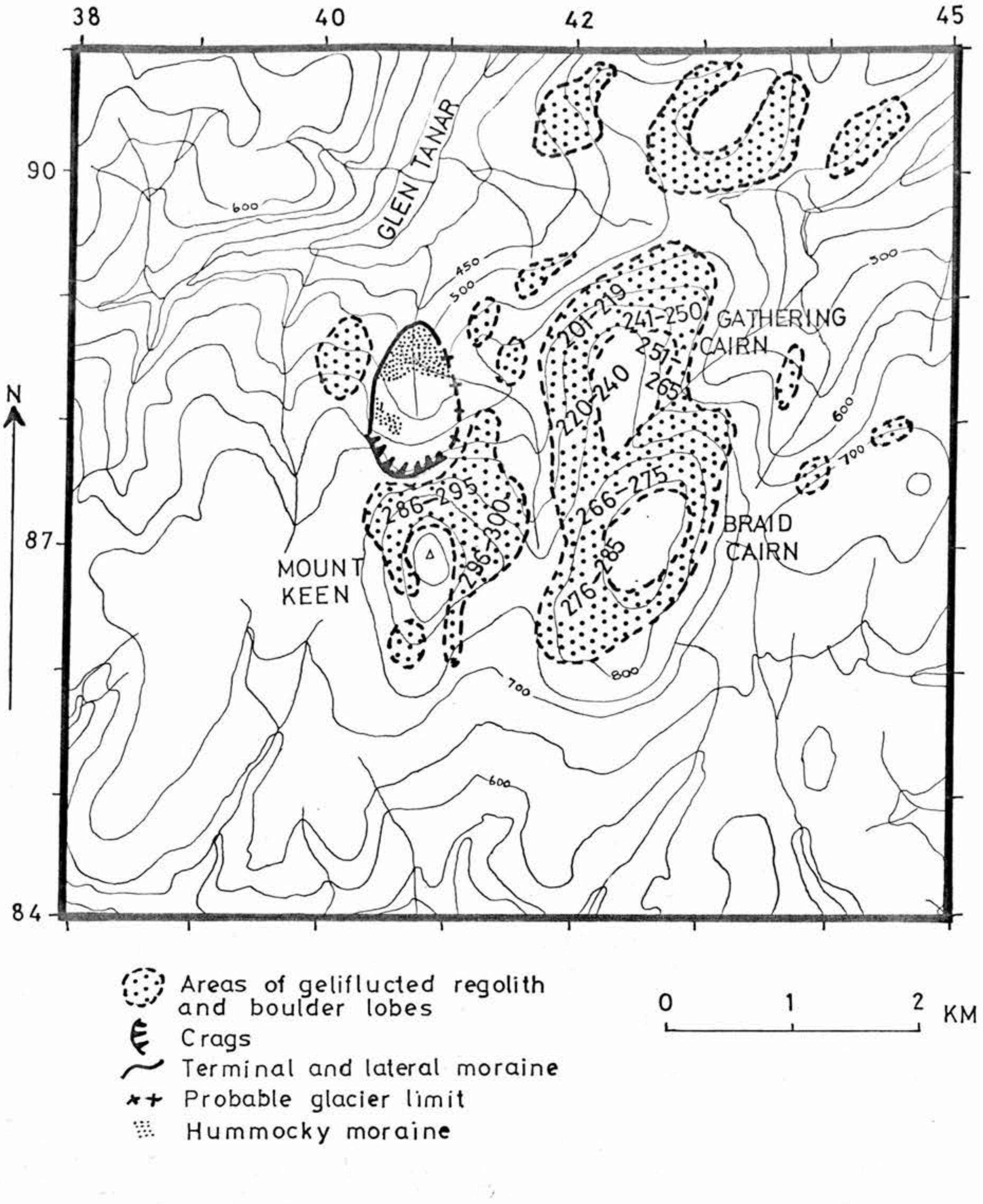
Sampling Procedures

Lobes were sampled from the flanks of individual hill masses. The field procedure involved 'contouring' the flanks of individual hills, walking a complete circuit, and examining all the lobes encountered. This method ensured that lobes of all sizes and forms would be examined, and allowed a wide range of slope aspects to be

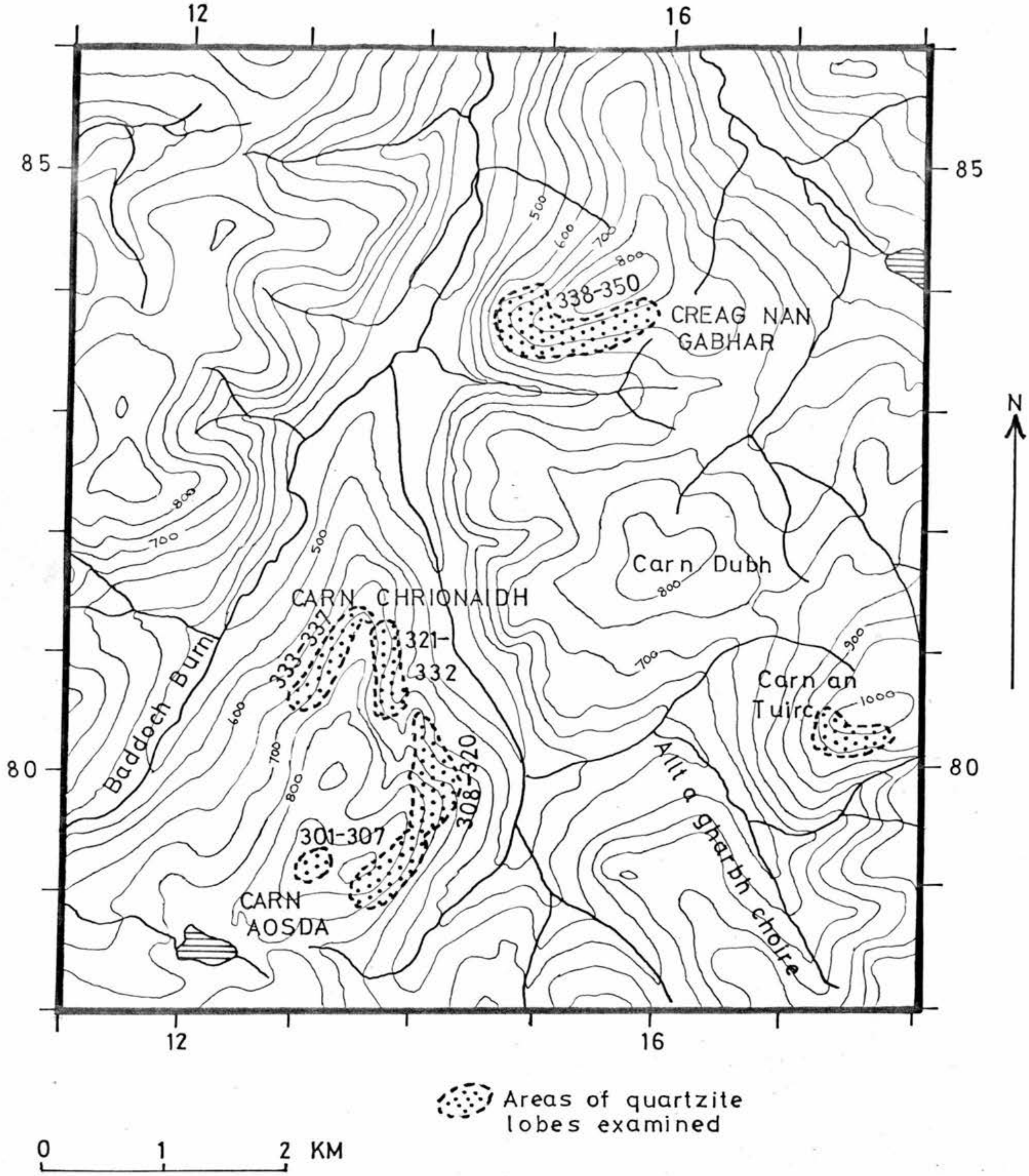


21
23
25
27
29
89
87
85
82
N
Cnapan Nathraichean
76-95
26-45
51-55
56-75
blackshiel burn
46-50
Meall an Tionail
1-25
Creag Liath
Meall Coire na Saobhaidhe
coire na ciche
148-154
143-147
Conachcraig
sandy loch
Cac Carn Beag
163-172
Cac Carn Mor
Meikle Pap
121-127
corrie of lochnagar
Eagle Ridge
155-162
173-182
188-197
198-200
96-120
loch nan eun
Stuic Buttress
Cuidhe Crom
Little Pap
128-142
glas allt
White Mounth
183-187
dubh loch
loch buidhe
Loch Muick
Areas of granite boulder lobes
Hummocky moraine
Lateral and terminal moraine
Probable Possible Readvan limits
Fluted moraines
Col meltwater channels

Map Figure 5.1a   The distribution of areas of lobate regolith, and location of sampled granite lobes in the Lochnagar study area



Map Figure 5.1b The distribution of areas of geliflucted regolith in the Mount Keen study area, and the locations of the lobe sampling areas



Map Figure 5.1c The location of the quartzite lobe sampling areas in the metamorphic part of the study area sampled. As previously stated, lobes usually occur in series, several individuals occurring side by side, their fronts approximately paralleling the contours. The steep frontal riser turns away upslope, forming steep sides to the lobe. Sides of adjacent lobes converge upslope to form a deep and narrow re-entrant. The last 'lobe' of a series is usually only partially developed, extending from the upslope termination of the side of the previous lobe as a short incomplete riser (Figure 5.12). These incomplete forms were not measured as no opposing sides were present.

When lobe-series at one level had been examined, lobe-series above were sampled, to the top of the hill. Many part-formed lobes were evident, and crenulated riser-walls that were incomplete, merging with the hillside and re-appearing. Thus, although there were many steep downslope-facing boulder walls or risers, relatively few well-developed, identifiable lobes, or terraces, were present. It became evident, during the field sampling period that lobes and terraces are idealised mass movement forms, identifiable, easily classified shapes among an infinite variety of 'riser-fronted' forms. Many problems arose in identifying the marginal forms (Figure 5.12, illustrates examples of boulder walls).

RESULTS

Part 1: The Distribution and Characteristics of Lobes

The Distribution of Lobes

One of the main aims of the lobe sampling studies was to assess the factors that limit the occurrence of periglacial boulder lobes in the study areas. Four of the fourteen measured parameters describe the topographic situation in which the lobes occur. A fifth factor, the position of the lobes in relation to the mapped limits of the presumed Loch Lomond corrie glaciers, is considered in detail in a later section (Age of Lobes).

The factors of interest here are the altitude of the lobe site, the aspect of the slope, the angle of the slope and the nature of the slope vegetation.

Altitude:

Lobes were sampled at altitudes between 580m and 1110m (Figure 5.2).

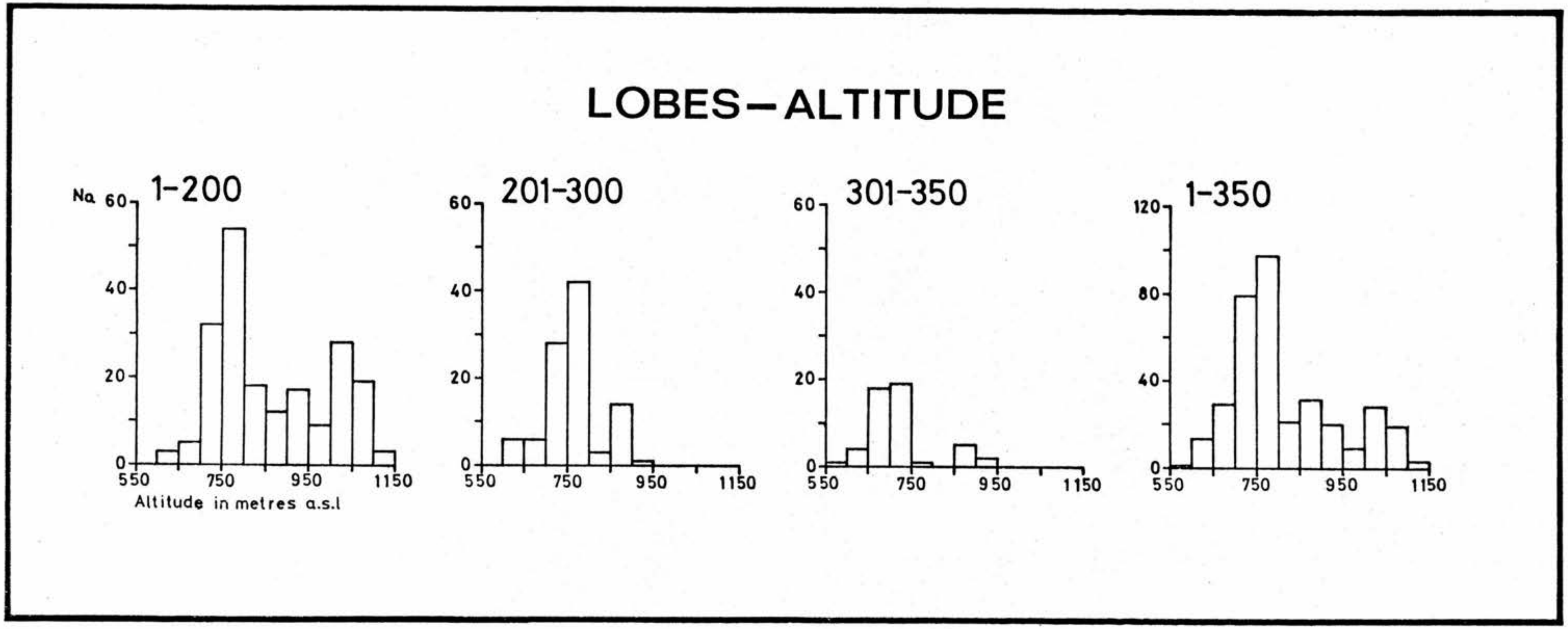

LOBES-ALTITUDE
1-200
201-300
301-350
1-350
No.
Altitude in metres a.s.l
0
20
40
60
80
120
550
750
950
1150

Figure 5.2

The lowest lobes in the granite areas occurred at about 640m. They were situated upon the north-west slopes of Gathering Cairn (NO 417890: Mount Keen Lobes 201-3, 241-3) and on the lower north-west slopes of Conachraig (NO 271868: Lochnagar Lobes 149, 151, 152). The highest examples in the granite areas occurred at about 1110m in the summit col of Lochnagar (NO 243858: Lobe 172), and at 970m near the summit of Mount Keen (NO 412869: Lobe 290).

Lobes in the metamorphic area ranged between 580m, on the eastern slopes of Carn Chrionaidh (NO 140807:Lobe 321) and 900m near the summit of Carn Aosda (NO 132794: Lobes 303, 304).

An upper limit to lobe development was presented by the available relief in each area. Lobes were found nearly to the summits of each of the highest peaks, mantling the convex summit edges until the slope declined to about 10°-12° (see Slope section).

Several factors operate to determine the lower limits of lobe developments in different situations. In many cases, the lower lobes on a hillside appear to descend below deposits of valley or basin peat. Examples of such lower limits are to be seen on the north-west flanks of Gathering Cairn(NO 417890) and the western flanks of Braid Cairn (NO 419872) of the Mount Keen Massif, and the western flanks of Meal an Tionail (NO 216875), and Cnapan Nathraichean (NO 217887), the head of Coir na Ciche (NO 271868), the eastern slopes of Cuidhe Crom (NO 264853: noted by Galloway, 1958, p.133) and the south-west slopes of Little Pap (NO 261843) of the Lochnagar Massif. In other situations the lobes terminate at an abrupt change of gradient onto a hillside bench, a high-level surface, or a flat valley floor. Such lower limits occur at the head of the Glas Allt Valley (NO 242853), the south-east end of Eagle Ridge (NO 250854), and the southern flanks of the White Mounth (NO 237837). Alternatively they were developed up to the edges of cliffs, as above the Dubh Loch (NO 237835), the Stuic Corrie slabs (NO240854) and on the north-east slabs of Cnapan Nathraichean (NO 226888). Several hills only had lobes developed on the upper slopes, suggesting that material was only available near summit, or that the lowest slopes were too steep as on Conachraig (NO 284872), Meikle Pap (NO 259861), Creag Liath (NO 244882) and Mount Keen (NO 413869).

In the metamorphic area the latter situation was the most common. Lobes were found to be developed upon the lower angle slopes around the summit areas, but were absent from the middle and lower steeper sections of the sharply convex slopes. Examination of steep stream valleys and gullies cut into the lower sections of these hills indicated that the quartzite debris mantle is present in quantity here (up to 5m deep in the gully on the western slopes of Carn Dubh at NO 144818 and NO 146807). Gradient appears to be the limiting factor to lobe development in these situations. Lobes occur frequently on slopes above 30^{o}. Steeper gradients appear to favour uniform sheet transfer of the debris mantle. Lobes were found on slopes of up to 33^{o} gradient in the metamorphic area (see Slope section). The lobes on the southern flanks of Creag nan Gabhar (NO 155837: Lobes 342-350) terminate at a break of slope, onto a bench-like feature, and the lobes at the summit of Carn Aosda (NO 132793: Lobes 303-7) terminate in the col feature between the twin summits of this hill.

In a few cases the downhill sequence of lobe-series terminate abruptly against, and above, the presumed limits of the Loch Lomond corrie glaciers. Such examples were observed in the summit col above the Stuic corrie (NO 240858: Photographs 5.2 and 5.5), in the Meikle Pap col (NO 258858) and above Loch Buidhe (NO 255830). This relationship has been observed by Sissons and Grant, 1972, p.90 and Sissons (1972, p.179; 1974b, p.325; 1974c, p.14; 1975, p.26; 1976, p.113). The significance of this phenomenon is discussed in detail in a later section (Age of Lobes section).

Galloway (1958, p.137) noted that lobes generally occur above about 600m in Scotland, and not infrequently at lower altitudes if peat is absent. Lobes were found above about 540m (Sugden, 1970a) or 550m (King, 1968) to 600m (Watt and Jones, 1948) or 670m (Metcalfe, 1950) in various parts of the Cairngorms. Kelletat (1970a) recently suggested that lobes are widespread in the Scottish Highlands between 500-1100m. Stone-banked lobes have been identified at altitudes between 670-750m in the Rhinog Mountains of North Wales, (Goodier and Ball, 1969) and above about 800m in Snowdonia (Ball and Goodier, 1970).

In Scandinavia stone-banked lobes are generally considered to occur in the 'Tundra Zone', in an altitudinal zone between the upper limit of the 'Forest Zone' at about 700m, to the lower limit of the 'Frost Shatter Zone' at about 1225-1275m or 1400m (Rapp and Rudberg, 1960; Rudberg, 1972). They are believed to be evenly spaced within their vertical range of distribution. Turf-banked lobes are associated with the lower levels of the tundra zone and the upper levels of the forest zone. According to Lundqvist (1962, p.49) the upper limit of sorted (stone-banked) solifluction steps (lobes) is probably merely the absence of soil in the frost shatter zone. Galloway (1958, p.133) believed that the abrupt upward cessation of stone-fronted lobes on the eastern slopes of Cuidhe Crom, Lochnagar (NO 264853) was due to the absence of fines at higher levels, the lobes passing up into a coarse block-field. Kelletat (1970b) held the view that a true frost debris zone is missing in Scotland.

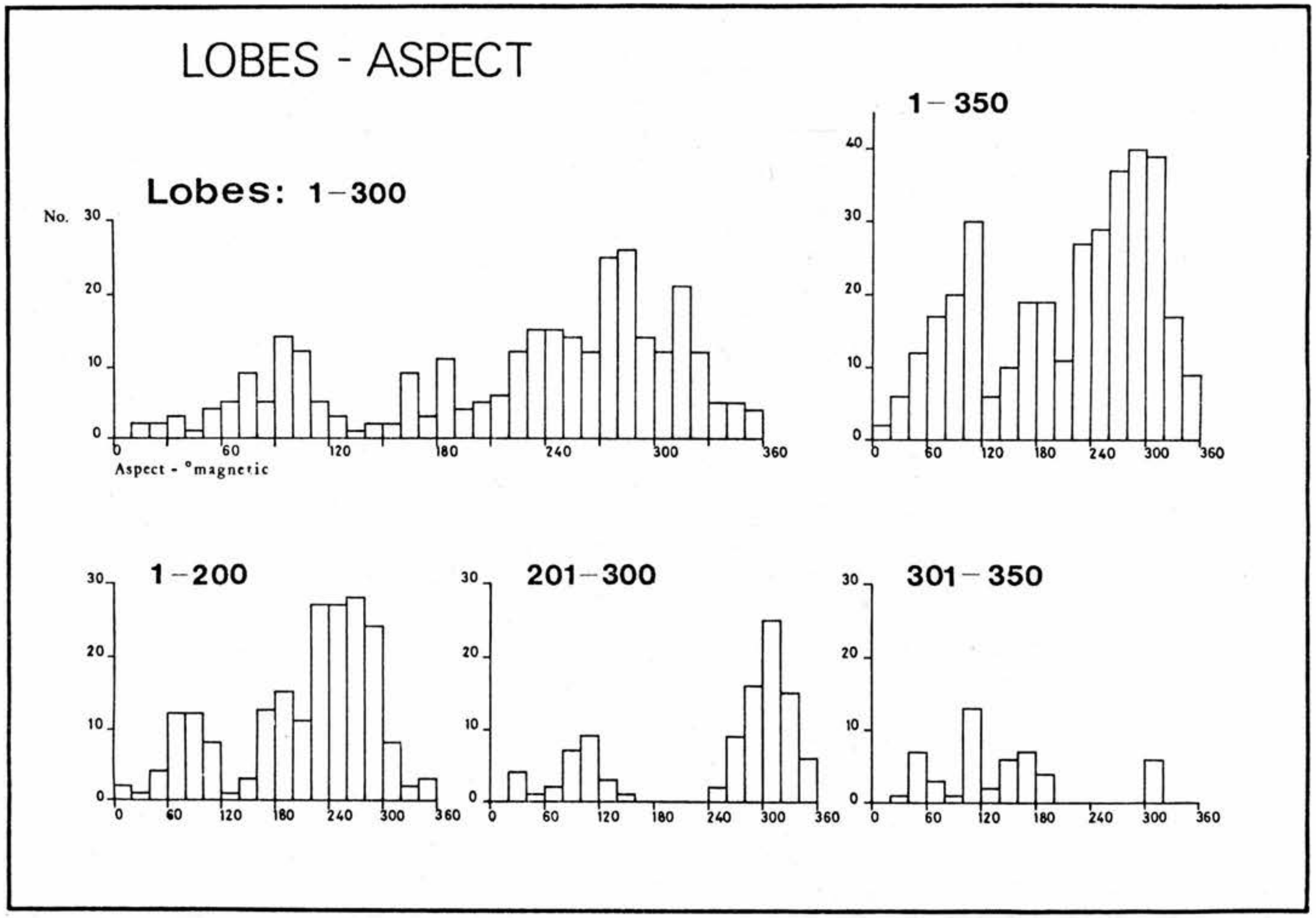
The observed lower limit of lobes, at around 580m, in the metamorphic area, appears therefore to be similar to that reported from other parts of Scotland and from Scandinavia. The observed upper limits, near the highest summits of the study area, are governed by the available relief, but lobes do not appear to develop higher than these altitudes in Scandinavia, where a frost-shatter or blockfield zone succeeds in the sequence of altitudinal zonation.

Aspect:

Lobes were not found to be restricted to slopes of any particular aspect or range of aspects; they were found on slopes of all aspects (Figure 5.3). They do appear to show a preference for slopes of a westerly aspect.

The majority of the granite lobes, about 73% (218), were developed upon slopes with a westerly aspect (between 180^{o} and 360^{o}). This is reflected by the mean aspect of 223.8^{o} for the total granite sample, but the wide dispersion is evident from the large standard deviation (87.4^{o}). Lobes in the granite area appear to prefer slopes between 220^{o} and 320^{o}, in which sector about 55% (169) of the sample occur. A second smaller peak in the distribution is apparent between 90^{o} and 110^{o} (9% or 27 examples).

This apparent preference could be a result of environmental conditions (formerly) favouring lobe development upon west-facing slopes as opposed to east-facing slopes, or it might only



LOBES - ASPECT
Lobes: 1-300
No.
30
20
10
0
60
120
180
240
300
360
Aspect - °magnetic
1-350
40
1-200
201-300
301-350

Figure 5.3

indicate the predominance of slopes of this aspect in the areas studied. To test this latter possibility, the relative frequencies of the total slope aspects available in the areas studied were estimated from the 1:10,000 Ordnance Survey maps. The results are presented in histogram form in Figure 5.5 with the distributions of the sampled lobes, expressed as relative frequencies (from Figure 5.3: 1-300) for comparison. The two sample distributions were statistically compared (Kolmogorov-Smirnov) and found to be significantly different at the 99% confidence level. This result suggests that the boulder lobes in the Mount Keen and Lochnagar granite areas have not developed similarly upon all the available slopes. They appear to have developed preferentially upon slopes of certain aspects, especially upon west-facing slopes.

Metamorphic lobes were found upon slopes of aspects from 32^{o} to 316^{o}, but mostly upon east-to south-facing slopes (32^{o}-198^{o}: mean 141.3^{o}) (Figure 5.3: 301-350). The relative frequencies of available slope aspects within the metamorphic study area were found to differ significantly, at the 97.5% level (Kolmogorov-Smirnov), from the observed distribution of metamorphic lobes, but the small size of the sample (50) does not allow reliable conclusions to be drawn about the distribution (aspect) of lobes in this area.

Within the Cairngorms different authors have variously observed that 'terraces', 'oval terraces' or stone-banked lobes are more abundant upon north—facing slopes (Watt and Jones, 1948; Galloway, 1958, p.131), on west-facing (as opposed to east-facing) slopes (King, 1968,p.95), or that they occur on slopes of any aspect (Metcalfe, 1950; Sugden, 1970a). Watson (1961) found solifluction deposits, with lobate forms, mainly developed upon north-and/ or east-facing slopes in the Plynlimon area of Wales. Similarly Pissart (1963b) concluded that solifluction lobes were most common on north-east slopes below persistent snow-banks. Crampton and Taylor (1967) found solifluction terraces best developed upon south- and west-facing slopes in South Wales.

On the Niwot Ridge of the Canadian Rockies stone-banked lobes were found to occur mainly upon south-and east-facing snow accumulation slopes (Benedict, 1970, p.176). Giant terraces were found best developed upon east-facing, leeward, slopes on Macquarie Island, but not so well developed on windward (west-facing) slopes (Taylor, 1955). Terraces were found dominantly upon south-facing slopes on Jan Mayen Island (Wilson, 1952).

Sorted steps are favoured upon west-facing slopes in Sweden by the increased precipitation on western mountain slopes, but in detail the 'steps' were often found to be dominantly located upon east-facing slopes of particular mountains (Lundqvist, 1962, p.48). Sernander (1905, p.58) only recorded 'solifluction steps' towards the southern semicircle.

The findings from other areas thus seem to differ in detail from the present facts. This difference is probably in part, if not wholly, due to a major difference in the type of features being described. Many of the features recorded by other authors are actually terraces. In most cases, as far as can be determined, the reported features are formed predominantly of fine-grained material that is capable of saturated flow. Thus the distribution of direct rainfall (as opposed to snow) precipitation is important (eg. Lundqvist, 1962, p.48), as also is the situation of these features below late-lying, leeward, slowly-melting snow patches that provide abundant moisture (eg. Sernander, 1905, p.58; Williams, 1957a, p.44, 1959b; Lundqvist, 1962, p.48; Rudberg, 1962, p.316; Raup, 1969, p.137). Lobes in the present study area are composed of large boulders, averaging 1m in diameter in many cases, with little evidence of interstitial fine material, as a result of which they are not capable of saturated flow (see Part 2: The Nature of the Lobes).

At the present day the prevailing winds blow from the south-west, causing snow to accumulate by redistribution upon north-east-facing slopes. A similar situation probably existed during the Loch Lomond Readvance period, when the 'south-wind snowstorm' (Manley, 1952, p.214-219; Sissons, 1974a, p.110) is believed to have contributed much of the snowfall, with south-west winds sweeping the snow off the summit-area (Sissons and Grant, 1972, p.92). It is concluded that the large granite boulder lobes are developed preferentially upon west-facing slopes that are subject to less snow-accumulation and late snow-lie, largely due to the insulating effects of such a cover inhibiting movement (c.f. Smith, 1960, p.78; Caine, 1963b, pp.176-177).

Slope Angle:

The boulder lobes examined were large features, particularly in the granite areas. They were formed by differential movement of the bouldery slope-regolith, and are, in consequence, a part of the hillslopes within the study areas . As a result difficulties were often encountered in attempting to define and measure the angle of slope upon which the lobes were situated. Slope angle readings had to be generalised down the crests of a flight of lobes (see map Figure 5.12).

Granite lobes were developed upon slopes between 10^o to 34^o gradient (Figure 5.4: 1-300). Metamorphic lobes occurred on slopes between 18^o to 33^o (Figure 5.4: 301-350).

Granite lobes were found to be most frequently developed upon slopes between 17^o and 25^o, within which range about 76% (229) of the sample occur. About 54% (163) are developed upon slopes between 18^o and 22^o. The mean slope for the granite sample is 20.0^o (standard deviation 4.22^o).

Metamorphic lobes appear to be developed upon slightly steeper slopes, with a mean slope of 24.4^o for the sample (standard deviation 4.63^o). 58% (29) of the metamorphic sample are developed upon slopes of 20^o to 26^o.

These findings are in general agreement with those of other workers investigating similar features. Turf-banked and mud lobes are usually found on shallower slopes.

Thus Galloway (1961b) reported a slope range of 8^o-20^o for stone-banked lobes on Ben Wyvis and 5^o-12^o for turf-banked lobes. On slopes of less than 15^o he believed stone-banked lobes become stabilised by vegetation. King (1968, 1972) found stone-banked lobes generally developed upon slopes of 20^o-35^o in the Western Cairngorms, but some occurred on slopes as little as 10^o. He believed that slope angle was more important in determining the presence of stone-banked lobes than altitude. Vegetation-covered lobes were usually developed upon 10^o-20^o slopes, but were found on slopes as little as 5^o and as steep as 30^o. Sugden (1970a - after King, 1968) believed that stone-banked lobes develop on

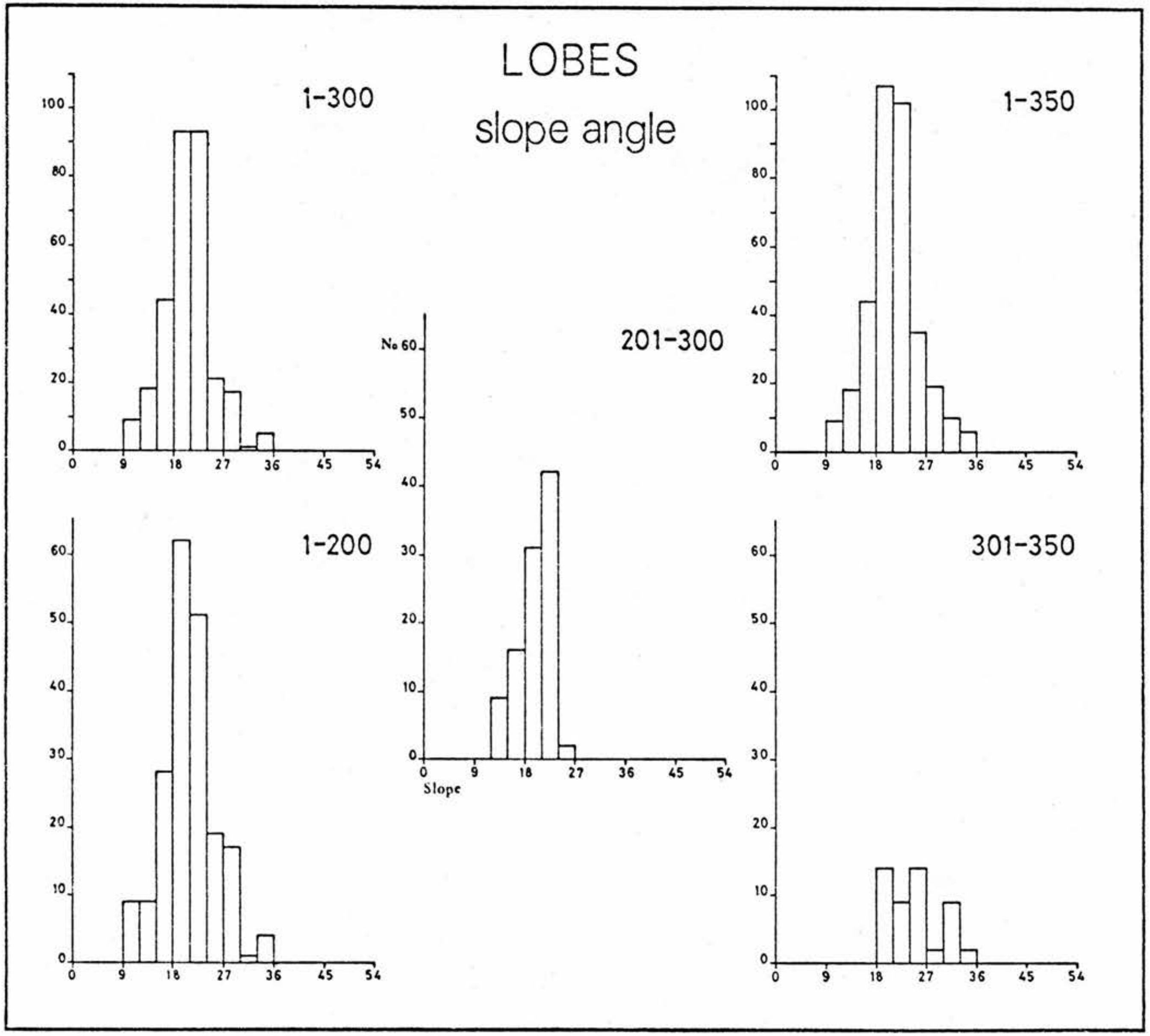


Figure 5.4

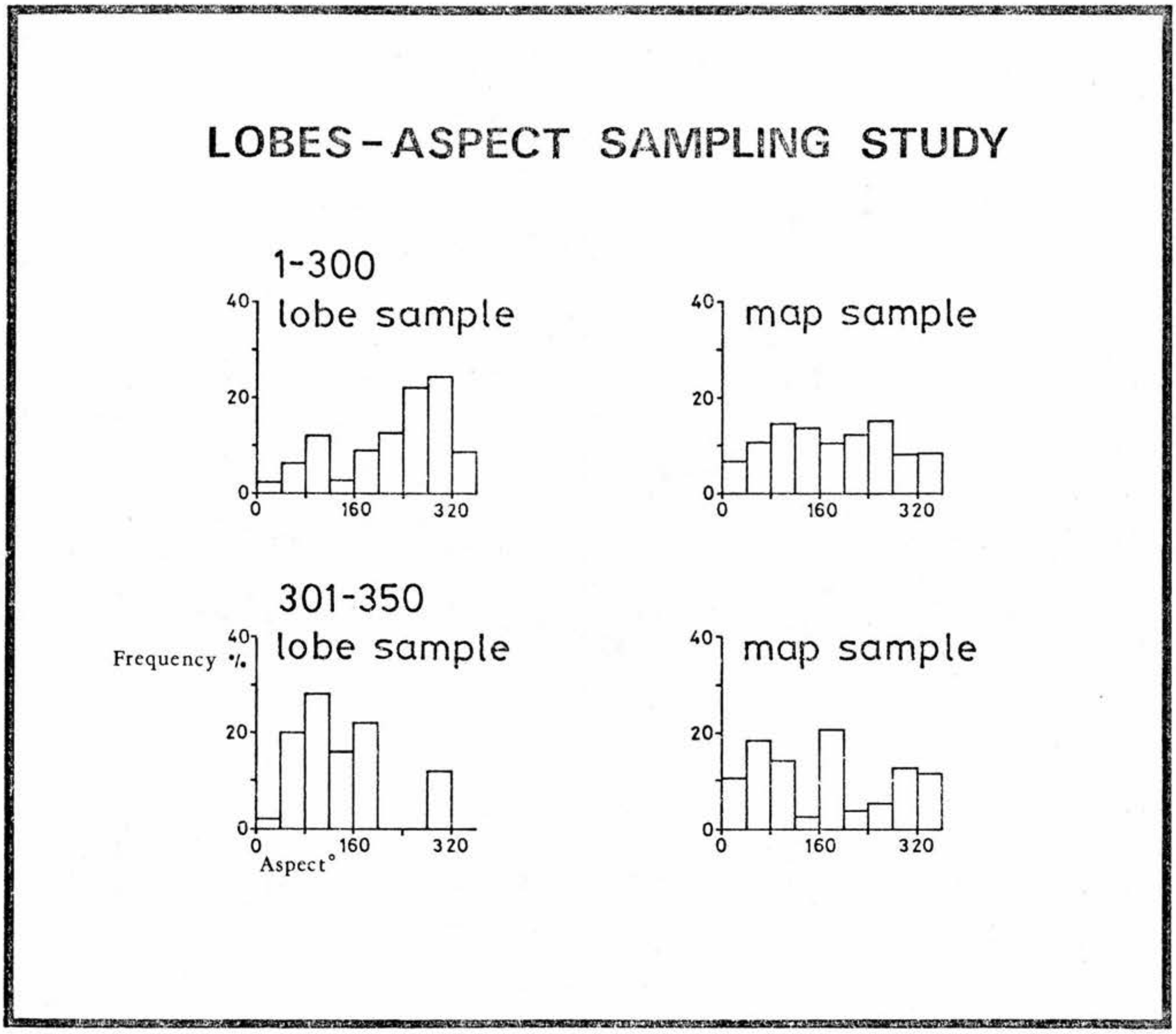
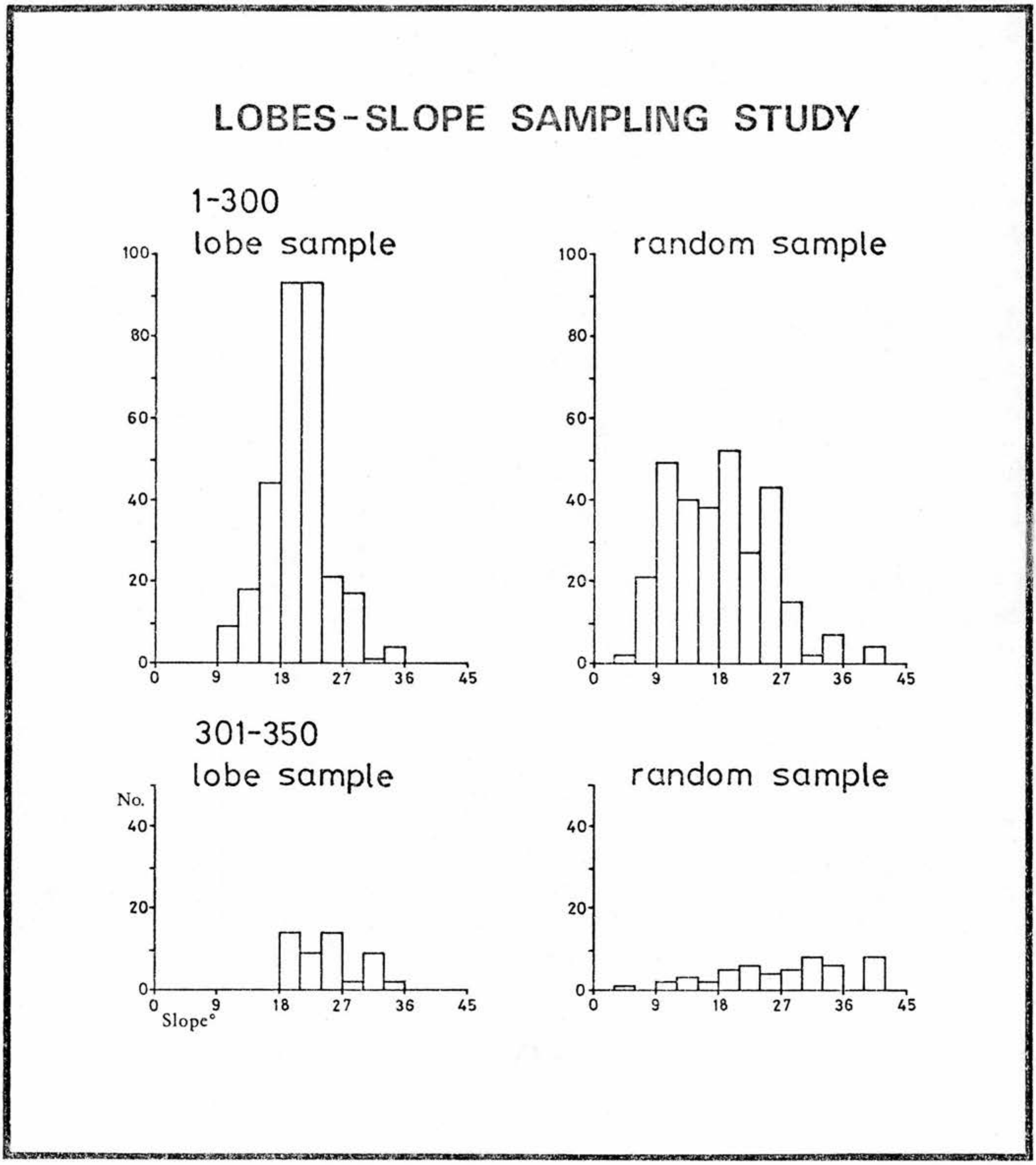

LOBES - ASPECT SAMPLING STUDY
1-300
lobe sample
map sample
301-350
lobe sample
map sample
Frequency %
Aspect°
40
20
0
160
320

Figure 5.5a



LOBES-SLOPE SAMPLING STUDY
1-300
lobe sample
random sample
100
80
60
40
20
0
0 9 18 27 36 45
301-350
lobe sample
random sample
No.
40
20
0
0 9 18 27 36 45
Slope°

Figure 5.5b

slopes of 20°-35° in the Cairngorms, but turf-banked lobes on slopes of 30°-35°.

Workers in other countries have reported a variety of lobate and terraced forms from a range of slopes. Thus lobate-terraces and sorted steps have been recorded on "very steep" slopes but often as gentle as 5°-10° slopes (Sernander, 1905, p.59: Sweden), stone-garlands on slopes ~~on slopes~~ of 5°-15° (Sharp, 1942: Yukon), lobate-terraces on 7°-20° slopes and soil lobes on 20° to at least 25° (Sigafoos and Hopkins, 1952: Alaska), garlands on 5°-15° slopes (Wilson, 1952: Jan Mayen Island), soliflual tongues on 15°-20° slopes (Jahn, 1958: Carpathians), congelifluction lobes on 3°-20° slopes (Dutkiewicz, 1961: Spitsbergen), garlands on slopes of 11° or 12° to 28° or 30° (Klatka, 1961b: Spitsbergen), soil-lobes on 20°- 25° slopes (Lundqvist, 1962: Sweden), stone-banked terraces and garlands on 15°-20° slopes and smaller block lobes on 10°-15° slopes (Jahn, 1967: Spitsbergen), festoon-like block fields on 30°-40° slopes (Perov, 1969: European Russia), solifluction lobes on 5°-15° slopes (King and Buckley, 1969: Baffin Island), and stone-banked lobes on slopes of 12°-24° (average 17°) (Benedict, 1970: Canadian Rockies).

Thus granite lobes in the present study were found on low angle slopes normally associated with finer-grained congelifluction or soil lobes (around 10°) to those occupied by festoon-like block fields (over 30°). In fact they occurred in almost all slope positions from near the base to near the summit. It is possible, therefore, that the granite lobe samples simply indicate the distribution of slopes within the study areas, rather than the slope angles favourable to lobe development. A random slope sampling technique was devised to sample slope angles from the 1:10,000 map in order to test this possibility.

The hillsides surveyed during the field sampling were delimited upon the map so that the map sampling could be contained within the same areas. A numbered grid was placed over these areas in turn, and the same number of random slope samples were gathered as had lobe samples from that area. Using a table of random numbers (in Hoel, 1971, p.p.398-399) coordinates were located at which the slope angle represented upon the map was calculated. Results of the random slope sampling test are presented in Figure 5.5 with the results of the granite lobe field sampling (from Figure 5.4: 1-300). The two sample distributions are statistically different (Kolmogorov-Smirnov) at the 99.9% confidence level. From this result it is tentatively concluded that the development of granite lobes is favoured upon slopes between 10^{o} and 34^{o}, more specifically between 18^{o} and 22^{o}; these slope angles are not the most commonly occurring gradients in the granite study areas. The two sample distributions from the metamorphic area are significantly different at the 95% confidence level. Thus, the metamorphic lobes appear to prefer slopes between 18^{o} and 33^{o}.

Slope Vegetation

The vegetation communities characteristic of the slopes in the study areas consist dominantly of heather, vaccinium and rhacomitrium. Vegetation is usually regarded as a very important component of the gelifluction process, often being capable of impeding saturated geliflual flow, giving rise to the distinction between 'free' and 'bound' gelifluction. Vegetation may be able to prevent gelifluction (eg. Wilson, 1952) or partly stabilise gelifluction slopes (eg. Polunin, 1934) by the binding action of its roots, or reduce the intensity of frost heave, particularly in the upper layers (15 cm or so) of the soil (eg. Raup, 1971,p.16), by insulating the soil from large and rapid changes of temperature (eg. Annersten, 1966). Conversely, the vegetation cover may retain water and so promote gelifluction (eg. Sigafoos and Hopkins, 1952). Washburn (1967, p.p. 43-44, 104-105) determined that vegetated slopes moved more than dry, unvegetated slopes in the Mesters Vig District of North-east Greenland.

It was concluded that vegetation does not act as a retaining structure in any of the examples observed, so consequently is not important in the formation of these lobes. The lobes were formed before the vegetation became established, because the vegetation was not found to be growing in any soil of fine debris components of the lobes, but upon a layer of peat established on the lobe tread (see Trench Studies section). Vegetation is characteristic of all the lobe treads observed but was rarely found growing upon the risers.

Only about 16% (33) of the Lochnagar granite lobes had evidence of well established vegetation upon the risers of these 27 were well-vegetated, and 6 had large vegetation clumps or islands on the risers. The remaining 73% (267) were almost completely unvegetated. Occasional plants or groups of plants were found in niches between some boulders of the risers. All the riser-boulders were characteristically covered with thick patches or crusts of lichens, and often with many mossy plants. In the Mount Keen granite area 18% of the risers had extensive vegetation growth; the riser-boulders were similarly thickly lichen covered.

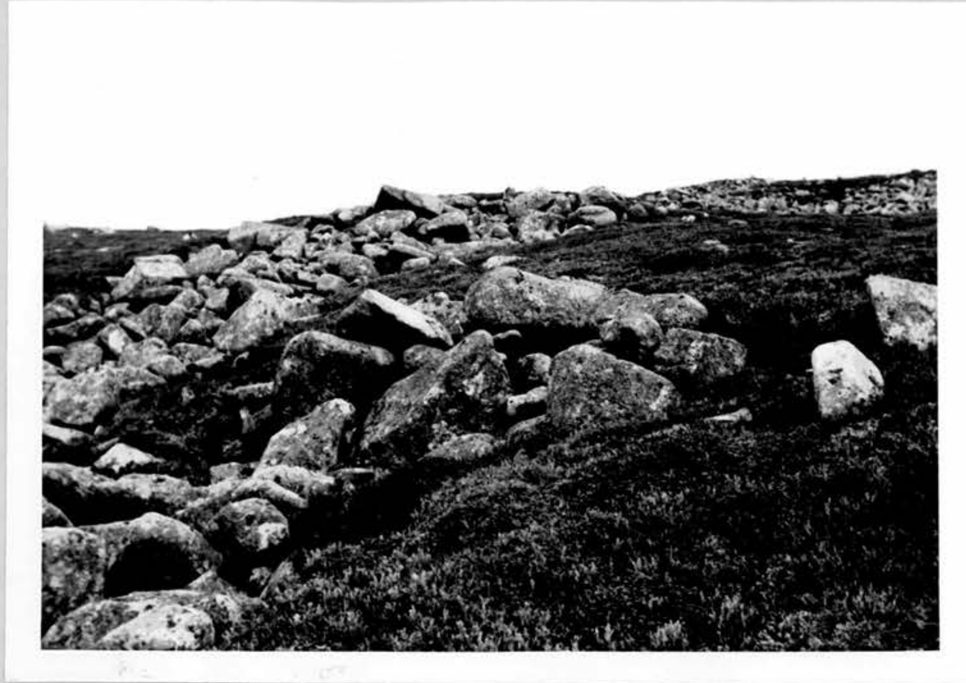
In a few lobe examples the treads were wet and marshy. This occurrence was rare. These lobes were found towards the foot of slopes, at the base of Conachraig in Coire na Ciche, and on the lower west-facing slopes of Cnapan Nathraichean. It was in these situations that the vegetated risers were most common, suggesting that fines are more abundant in foot-slope situations, and that springs emerge at the base of these otherwise dry slopes. Large boulders protruded through the vegetation-covered risers and the wet surfaces of these lobes, so they were not pure soil lobes.

Lobes in the metamorphic area were similarly vegetated. They all had well vegetated treads, but only 38% had vegetation developed to any extent upon the risers. Lichens were less common upon the quartzite debris of the risers than upon the granite boulders.

The Characteristics of Lobes

The surface form and size of the several lobe facets are summarized by 10 of the 14 measured parameters. These measurements are considered to describe two main elements of a lobe, the riser and the tread.

The riser is perhaps the most diagnostic feature of a lobe. It is the presence of a raised wall or riser upon a slope that indicates the presence of the downslope edge of a gelifluction mantle. A straight or irregular front characterises a terrace, but a sharply curved riser, with side-risers extending upslope, delimits a lobe. The riser was investigated at its downslope edge only, at the front of the lobe. Variations of the height and angle of the side-risers were beyond the scope of this present investigation: only their upslope extent was measured. Basically, the important features of the riser are its angle of declivity and its length. Associated with these measures are the angle of the ground



PHOTOGRAPH 5.3 Granite lobes on the flanks of Gathering Cairn (Mount Keen) illustrating the convex lobe treads with their steeply sloping forward portions, and the raised riser re-entrants (Lobes 201 and 202 fore-ground).

PHOTOGRAPH 5.4 The riser of granite Lobe 206 on the flanks of Gathering Cairn (Mount Keen).

immediately below the riser and the thickness of the lobe-layer. Both of these latter factors cause the riser to be distinct.

Features of the lobe tread are its gradient, width and total length. Also the length of the right-hand and left-hand side risers were considered to be important in delimiting the extent of the tread that was situated between raised risers.

The lithology of the lobes is dependent upon the area in which they are situated, but imparts distinctive characteristics to the lobes.

The Riser

Riser Angle:

The gradient of the steep frontal wall of each lobe was measured, in every case, at the front of the lobe from a point approximately at the mid-point of the curved front down the line of maximum slope (see map Figure 5.12).

The angle of the lobe risers ranged from 15^{o} to 45^{o} in the granite areas (Figure 5.6: 1-300) and from 22^{o} to 54^{o} in the metamorphic area (Figure 5.6: 301-350). In no instance was a riser found to be overhanging or bulging as in turf-banked lobes (eg. Taber, 1943, p.1461; Williams, 1957, p.42; Jahn, 1958, 1967, p.213; Raup, 1969; Benedict, 1970, p.172).

The risers of granite lobes most commonly had angles of between 24^{o} and 35^{o} (83%: 249); compared with 27^{o} to 41^{o} (76%: 38) in the metamorphic area. The mean angle of the granite risers is 28.7^{o} (standard deviation 4.6^{o}), and of the metamorphic ones 34.2^{o} (standard deviation 7.3^{o}). As might be expected, the range of slope angles is less than the range of riser angles in both the granite (10^{o} to 34^{o} compared with 15^{o} to 45^{o}) and metamorphic (18^{o} to 33^{o} compared with 22^{o} to 54^{o}) areas. Similarly the mean slope angles are less than the mean riser angles (20.0^{o} compared with 28.7^{o} in the granite area; and 24.4^{o} compared with 34.2^{o} in the metamorphic area) in both areas.

Few authors have reported the angles of boulder risers from lobes.. A limited amount of information is available for the risers of turf-banked lobes, which generally seem to be less steep than boulder risers.

Galloway (1958) recorded angles of 10^{o} to 20^{o} for the boulder

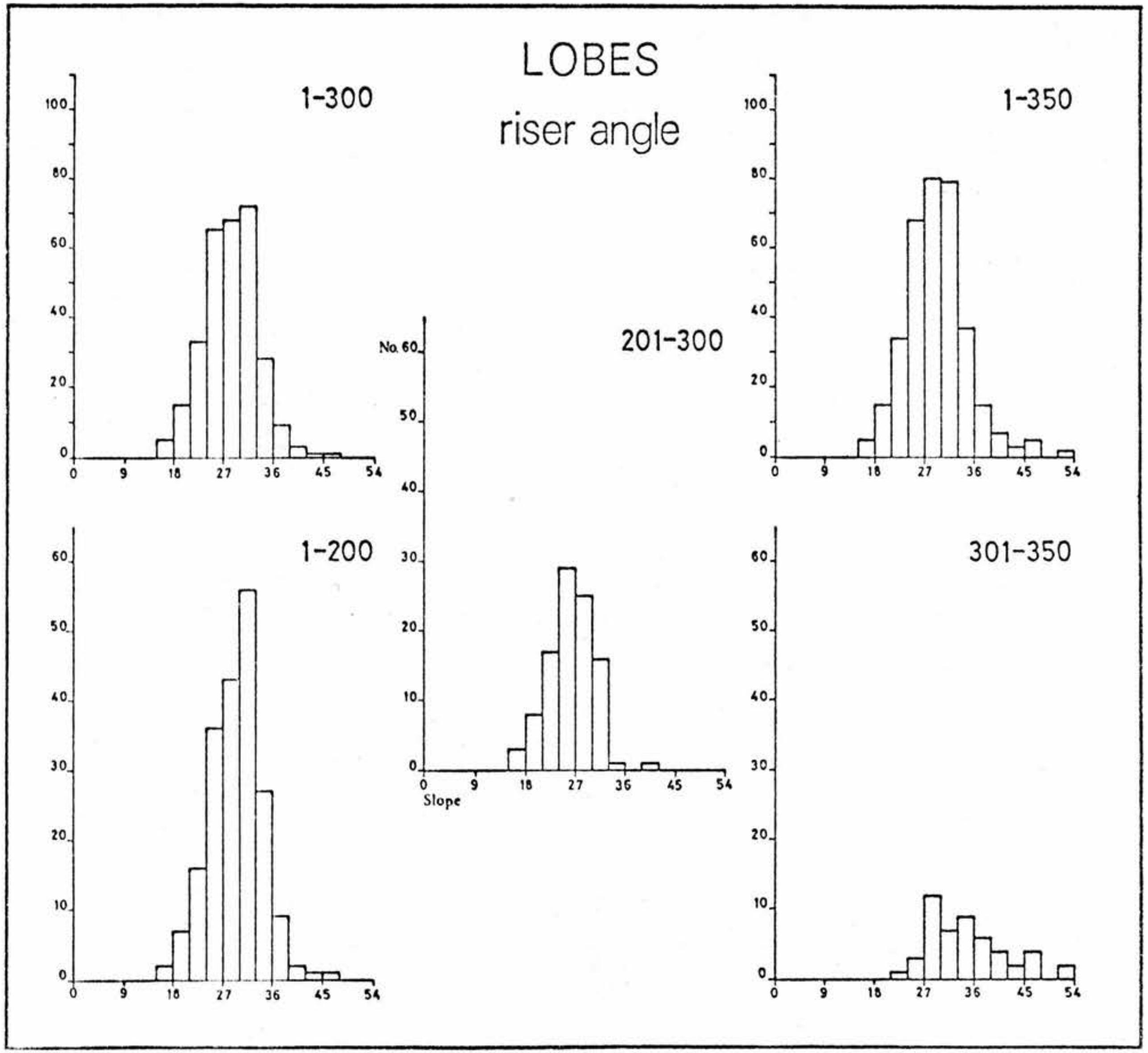

LOBES
riser angle
1-300
1-350
201-300
1-200
301-350
No. 60
Slope
0
9
18
27
36
45
54
0
20
40
60
80
100
10
30
50

Figure 5.6

risers of stone-banked terraces from the White Mounth of Lochnagar. King (1968) reported an average slope of 45° (p.99) for the risers of stone-banked lobes, and about 45° for the risers of vegetation-covered lobes in the Western Cairngorms.

Stone-banked lobes and terraces in the Canadian Rockies were recorded with riser angles of 20° to 50° (Benedict, 1970). Turf-banked lobes had riser angles of 10° to 35°, and turf-banked terrace risers were 10° to 50°, but were rarely bulging or over-hanging. Vegetation terraces on Macquarie Island had fronts at about 30° (Taylor, 1955) and vegetation-banked terraces on Jan Mayen Island had fronts of a similar angle (Wilson, 1952).

The angle of the lobe riser will depend upon a variety of factors including the size of the material, the influence of a binding vegetation layer (in the case of vegetation-banked features), the angle of the slope and possibly the thickness of the lobe layer and the slope situation (with respect to aspect, moisture concentration, late snow-lie, and other factors). The influence of some of these is investigated in a later section (Part 3).

Angle Below:

The angle of the slope facet immediately below the riser of each lobe was measured in order to establish the difference in angles between the riser and the ground onto which it has encroached. It was also hoped to investigate the possibility that lobes encroached onto ground that had a lower gradient than the general slope, thus that lobes developed preferentially in areas where the slope gradient decreased.

The angle below each riser was measured at each site; only the immediate ground, for about 5m in front of the base of the riser, was considered. In many cases the angle below was not a section of 'open slope', not covered with lobes, but often the upper portion of the tread of a lower lobe in a lobe sequence down a hillside. Occasionally the angle below was the forward part of the tread of a lower lobe: as in the case of lobe No.177 encroaching onto lobe No.178, so the angle below of lobe 177 is the surface angle of lobe 178. Thus the lobe-layers were commonly superposed, one sheet over-riding the next sheet below (c f. Porter, 1966; the

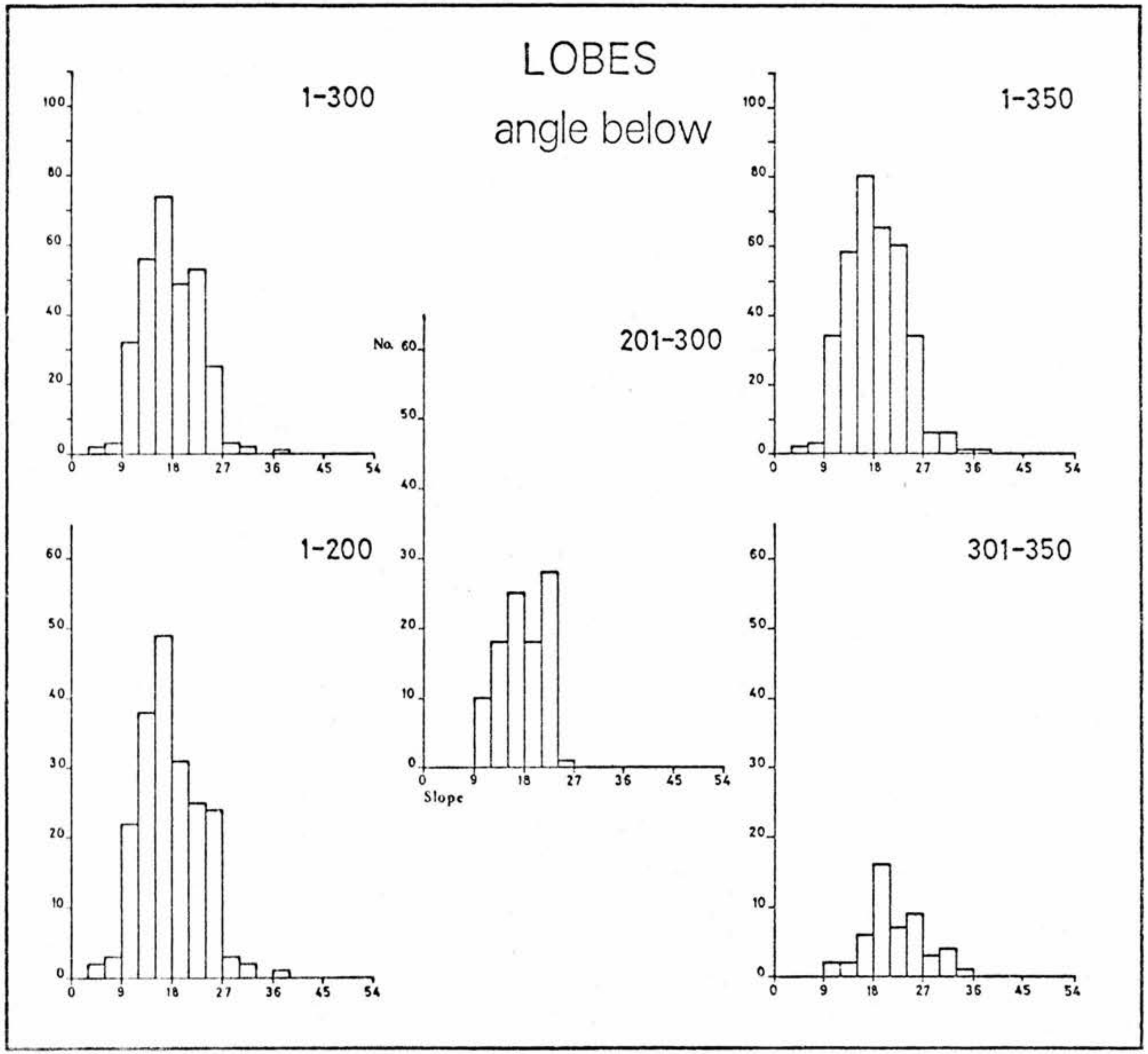

LOBES
angle below
1-300
1-350
201-300
No. 60
Slope
1-200
301-350
0
9
18
27
36
45
54
0
20
40
60
80
100
10
30
50

Figure 5.7

Anaktuvuk Pass, Central Brooks Range, Alaska). It was not unusual for the front of one lobe to have moved down onto the side tread of a lobe below, or onto the re-entrant formed by the two converging sides of two lobes below (c.f. Sharp, 1942, Figure 1, p.277). In this situation it was usually difficult to decide what actually comprised the angle below. This latter occurrence, the axis of one lobe being to the side of one below, or between two below, suggests that the lines of concentration of flow down which or at which the lobes develop, are different for the two layers.

Angles of the ground below the risers of granite lobes ranged from 5° to 32° (Figure 5.7: 1-300) with a mean slope of 17.3° (standard deviation 5.0°). About 91% (274) of the sample occurred between 10° and 25°. The range of slopes and mean slopes below granite risers is smaller than the range of slopes and mean slopes measured in the granite areas (5° to 32° compared with 10° to 34°, and 17.3° compared with 20.0°) .

Angles of the ground below the risers of metamorphic lobes ranged between 11° to 34° (Figure 5.7: 301-350), with a mean slope of 21.4° (standard deviation 5.4°). A majority of the sample (64%: 32) occurred between 18° and 26°). The angle of the ground below the risers of metamorphic lobes appears to be essentially steeper than that below granite lobes (11° to 34° compared with 5° to 32°), a difference reflected in the different mean slopes (21.4° compared with 17.3°).

There is no indication in any reports by other authors of the angle of this slope facet in other areas. Its value is perhaps represented by the slope angles quoted.

<u>Riser Length</u>:

The length of the exposed riser of each lobe was measured down the front of the lobe, in the line of the lobe-axis. Difficulties were often encountered in determining the top and base of the riser. There was usually found to be a well-defined break of slope at the base of the riser, the angle of the ground below the riser usually being less steeply inclined than the riser, so this niche formed by the two slope facets was identifiable as the base. The top was usually more difficult to define. Several criteria often had to be

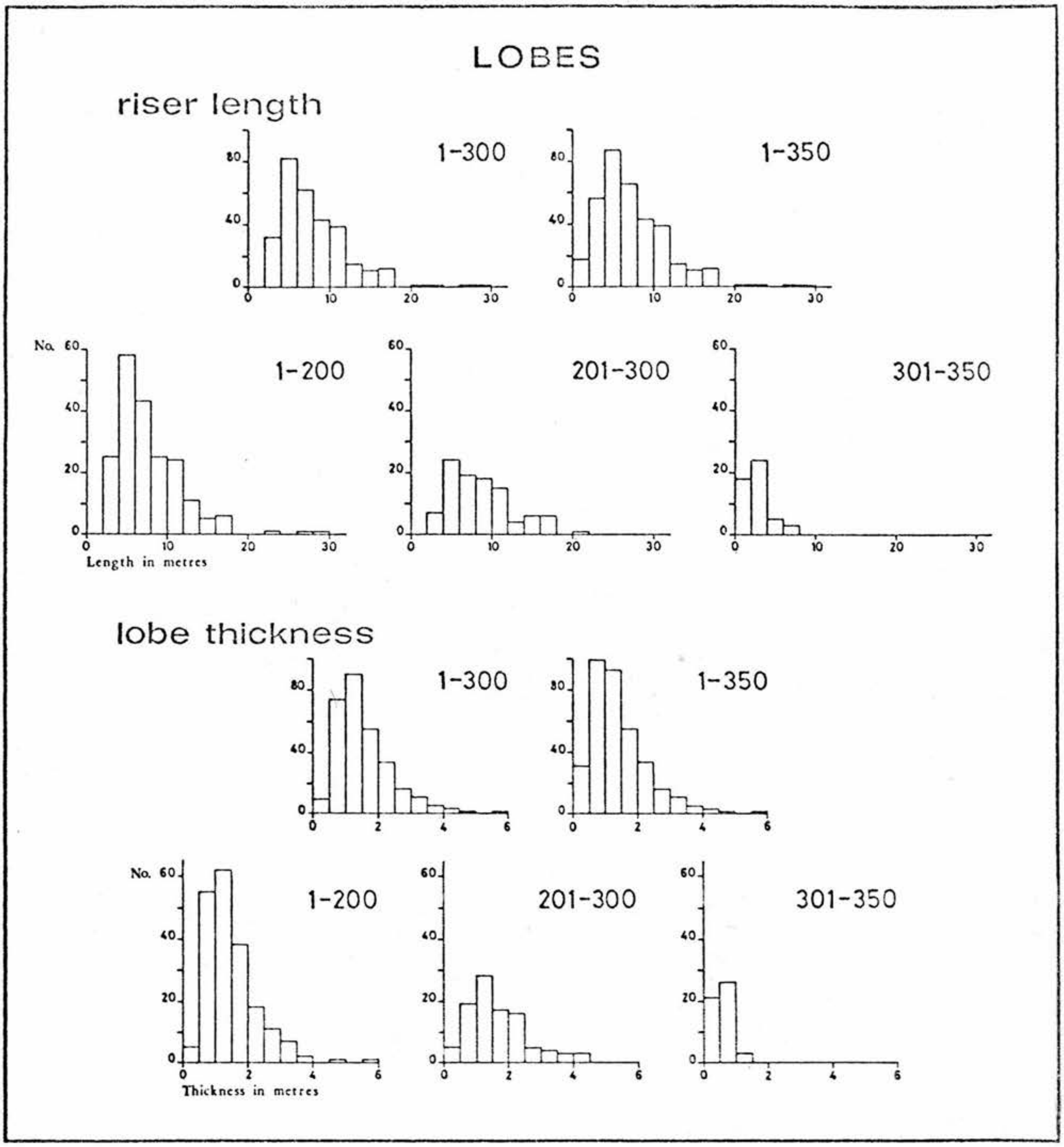

LOBES
riser length
1-300
1-350
1-200
201-300
301-350
No.
Length in metres
lobe thickness
1-300
1-350
1-200
201-300
301-350
No.
Thickness in metres

Figure 5.8

applied in different circumstances. The long profile of lobes is curved, the curve being shallow upslope but steepening towards the front of the lobe, at which point the profile is often rounded; thus the riser does not usually begin as a sharp increase of slope from the shallower surface angle of the tread. It was often possible to locate a point where a sharp change of gradient did occur. Otherwise, as the treads were vegetated and the risers usually bare, the margin of the tread vegetation assisted. Often the side-risers were steeper or better defined than the front-riser so the top of the front riser could be extrapolated from the sides.

It was found that many lobes had long frontal risers, declining at relatively low angles, and apparently 'spilling-out' onto the ground ahead. The side-risers were almost always steep and well-defined; thus the long-low riser of the front indicated by the measurements often gives a rather misleading impression of a lobe's appearance in the field.

Riser lengths of granite lobes ranged from 2.0m to 28.4m (Figure 5.8: 1-300). The majority of the examples occurred within a smaller range. Thus about 86% (258) were between 2.0m and 11.8m, and about 48% (144) between 4.0m and 7.9m (Figure 5.9). The mean riser length is 8.0m (standard deviation 4.1m).

Risers in the metamorphic area were generally shorter, ranging from 0.6m to 7.0m in length (Figure 5.8: 301-350). The majority (84%: 42), were between 0.6m and 3.9m long, and 48% (24) were between 2.0m and 3.9m long. The mean riser length is 2.7m (standard deviation 1.4m).

It is difficult to compare the results of this survey with those reported from other areas as no indication is given of the meaning of "height of the riser". The height of the riser-crest above the slope surface is calculated in the succeeding section, and these values are compared with other workers' findings.

<u>Lobe Thickness:</u>

This measure was calculated from the riser angle, riser length and angle below values, and approximates to the thickness of the debris layer forming the lobe. The measure also indicates the height of the riser crest above the slope surface. As previously stated (Riser Length section) the long-profile of a lobe is convex upwards; thus the figure calculated for the thickness only estimates the thickness of the layer at a point considered to be the riser crest. The lobe layer appears to thicken slightly upslope. Another assumption is that the surface upon which the lobe is developed, described by the angle below, continues uniformly under the lobe.

Lobe thickness in the granite area ranged from 0.3m to 5.9m (Figure 5.8: 1-300). The majority of granite lobes were less than 2m thick: 73% (219) were between 0.5 to 0.9m thick. The mean thickness of granite lobes was calculated to be 1.5m (standard deviation 0.86m). Metamorphic lobes were, on average, thinner than granite lobes. The thickness of metamorphic lobes ranged from 0.2 to 1.3m. A majority (60%) were 0.5m or less. The mean thickness was 0.55m (standard deviation 0.24m).

The height of the riser of lobes and terraces is the most frequently quoted size parameter in the literature. Previous examinations of the heights of risers of the lobes on Lochnagar have estimated them to be up to 6m high (Galloway, 1958)., from 2 to 5m high (Grant, 1971) and up to 4.6m (15ft) high (Fyffe,1968). Galloway (1958) reported stone-fronted lobes from 1. to 5m high on the slopes of Ben Wyvis. King (1968) reported risers of stone-banked lobes up to 4 or 5m high in the Western Cairngorms, and risers of vegetation-covered lobes up to about 1m. Metcalfe (1950) also working in the Cairngorms observed "retaining banks" from 1 to 4m high. The risers of stone-banked lobes have been reported up to 1.5m high in the Mamore Forest area (Whyte, 1970) and from 1 to 3 m high in Snowdonia (Ball and Goodier, 1970).

Earth lobes with fronts up to 5m high have been observed in the Faeroe Islands (Jorgensen, 1972), and boulder walls of lobe fronts up to 5m high in the arctic (eg. Jahn, 1967; Bird, 1974, p.706). Gelifluction lobes are usually less than 2m high (eg. Williams, 1957a; Porter, 1966; Price, 1970; Harris, 1972,1973) and often only up to 1m (eg. Sharp, 1942; Dutkiewicz, 1961; Tivy, 1962; Kallander, 1967; Washburn, 1967, p.73; Ball and Goodier, 1970; Archer and Simpson, 1973). They may reach 6m or more high in the arctic, but usually average 1 to 2m (Price, 1972), similar in size to the features examined in the present study.

King (1968) found that turf-banked lobes were the smallest type of lobe occurring in the Western Cairngorms. Both turf-banked and vegetation-covered lobes were generally lower than stone-banked lobes. Conversely, Benedict found that the fronts of stone-banked lobes in the Colorado Front Range were rarely more than 1m high, but the fronts of turf-banked lobes ranged from 0.5 to 3.5m high.

Examination of these results from other areas shows that both stone and earth lobes can reach heights of up to 6m, about the height of the largest lobe in the present study. Thus the largest lobes found in the granite areas are not unique in the large height of their risers, but they are certainly among the largest reported and so are unusual. The majority of the granite lobes, at less than 2m high, are similar to the sizes most commonly reported.

Dylik (1969, p.390) observed that the thickness of lobes frequently increases towards the base of the slope. In general this relationship does not hold in the granite or metamorphic areas studied here. Lobe thickness does not show a direct linear correlation with altitude (see The Influence of Terrain Factors, Part 3). In detail, transects down individual slopes revealed that lobes do not necessarily increase in thickness downslope (Table 5.A).

TABLE 5.A

The Thickness of the Lobe Layer Down Selected Slope Profiles

Lobe No.	Thickness (m)	Approx Alt. (m)
Cnapan Nathraichean, S.W.Slopes		
41	0.6	0780
40	0.5	0770
31	0.6	0730
27	1.9	0710
Cuidhe Crom. E. Slopes		
105	2.7	1000
103	3.9	0990
100	1.1	0860
102	0.8	0840

Braid Cairn, N.W.Slopes		
238	0.8	0780
235	2.3	0770
234	1.0	0760
233	1.6	0750
223	2.5	0720
224	3.5	0720
Braid Cairn, N,W.Slopes		
250	1.4	0770
248	4.1	0760
247	1.7	0680
245	0.5	0660
202	2.4	0640

Summit Col, W.facing			Carn Chrionaidh, N.E.Slopes		
171	1.1	1080	325	0.3	0700
166	0.9	1050	324	0.4	0660
165	2.3	1040	323	0.5	0620
164	2.0	1030	322	0.5	0610
			321	0.5	0580

A tendency to increasing thickness downslope was apparent from the transects down the south-west slopes of Cnapan Nathraichean, in the Summit Col, and on the north-east slopes of Carn Chrionaidh. On the east-facing slopes of Cuidhe Crom the higher lobes were thicker than the lower lobes. On the north-west slopes of Braid Cairn anomalously thick lobes occurred towards the top of the two transects. Thus it is concluded that the thickness of the lobe layer is not directly a function of the altitude of the lobe, nor does it tend to increase or decrease uniformly up or down selected slope profiles.

The Tread

Angle of the Surface:

The long-profiles of lobes tend to be convex upwards, becoming steeper near the riser, and gently fading into the slope above in an upslope direction. Any simple measure of the gradient of this surface must be a generalised gradient. For the purposes of this study the angle of the surface was taken from a point opposite the shorter of the two lobe side-risers, down the axis of the lobe to the crest of the riser. Thus the results refer to the steeper frontal part of the lobe surface.

The surface of granite lobes ranged from 9^{o} to 36^{o} (Figure 5.9: 1-300), with a mean of 20.0^{o} (standard deviation 4.9^{o}). The majority of lobes (78%: 233) had surfaces between 15^{o} and 25^{o}.

Metamorphic lobes had surfaces between 15^{o} and 32^{o} (Figure 5.9: 301-350), with a mean slope of 22.8^{o} (standard deviation 3.6^{o}).

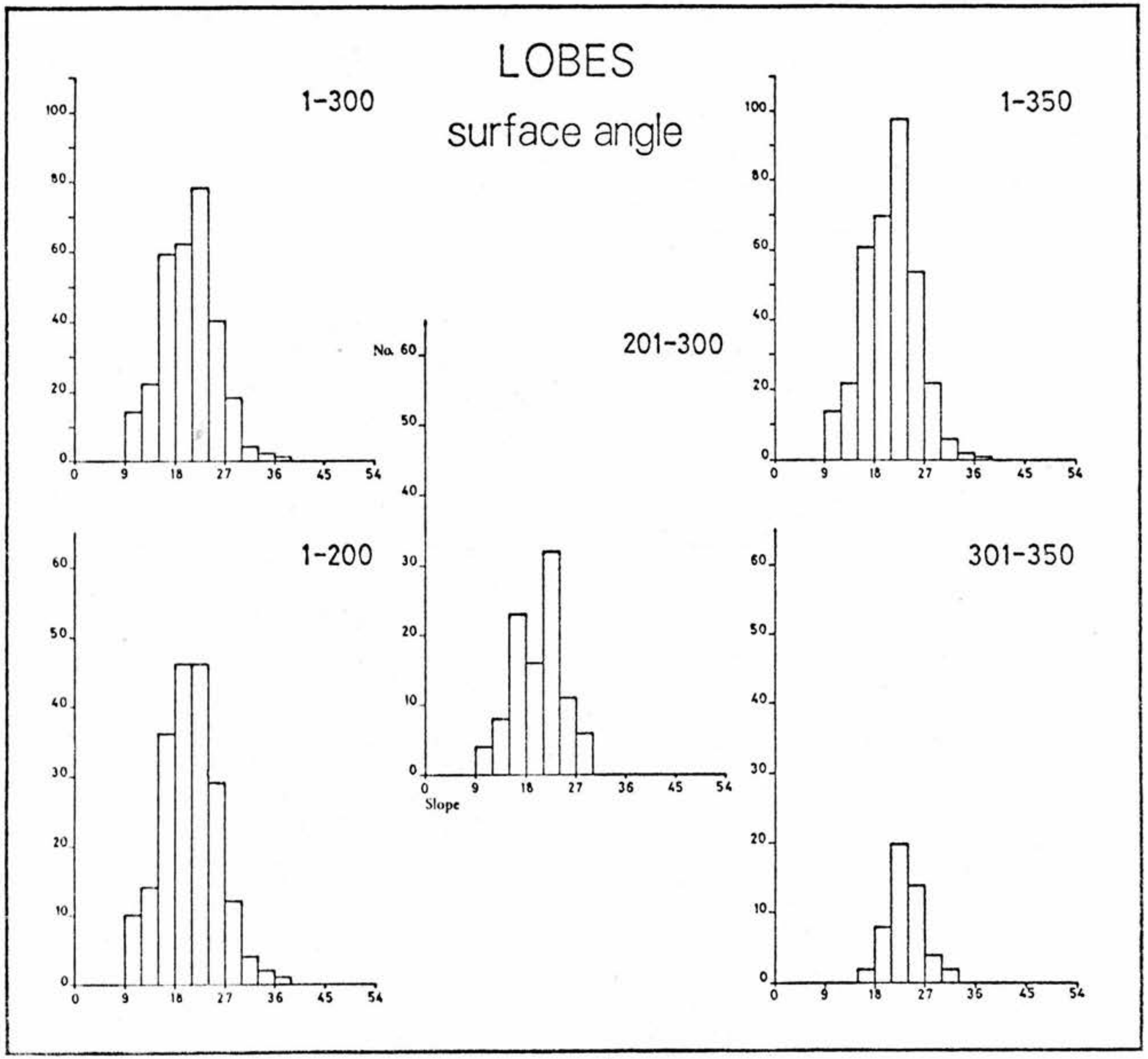

LOBES
surface angle
1-300
1-350
201-300
1-200
301-350
No.
Slope
0
9
18
27
36
45
54

Figure 5.9

Surfaces were mostly 84%: 42) between 18^{o} and 25^{o}. The results suggest that the angle of the surface of the metamorphic lobes is almost the same as that of granite lobes.

Previous estimates of the surface gradient of boulder lobes in Scotland are few. Galloway (1958) stated that the surfaces of terraces on the south face of White Mounth sloped at only a few degrees. Sugden (1970a) suggested that the treads of stone-banked lobes in the Cairngorms sloped at less than the overall slopes, and Metcalfe (1950, p.49) reported that the "platform of oval terraces" was typically sloping at 15^{o}.

The surfaces of lobes from other areas appear to be generally less steep than those measured here, possibly reflecting the different form of the features concerned, or possibly because other authors measured the upper surface of the lobe and not the steep frontal portion as here. Thus other workers have reported turf-banked lobes with treads of 2^{o} to 14^{o} (Benedict, 1970), earth lobes with surfaces of about 5^{o} (Jorgensen, 1972(, gelifluction lobes with tread slopes of about 12^{o} (Raup, 1969), and stone garlands with surfaces of 2^{o} to 3^{o} (Sharp, 1942).

Lobe Width:

It was found that lobes usually tapered towards the front, that is, narrowed downslope (Map Figure 5.12). The width was measured, in all cases, orthogonally to the lobe axis at a point opposite the shorter of the two lobe side-risers. This was the highest point upslope at which two opposing sides were present, and so at which a true width could be measured.

Lobes in the granite area ranged between 3.9m and 33.3m wide (Figure 5.10: 1-300), with a mean width of 14.8m (standard deviation 5.5m). About 83% (250) of the granite lobes were less than 20m wide (3.9 to 19.9m).

Lobes in the metamorphic area were generally narrower, ranging from between 3.9 and 10.4m in width (Figure 5.10: 301-350). The mean width of the metamorphic lobes was 6.3m (standard deviation 1.6m).

The width of lobes is the most frequently quoted lobe size parameter, after the riser height, in the literature.

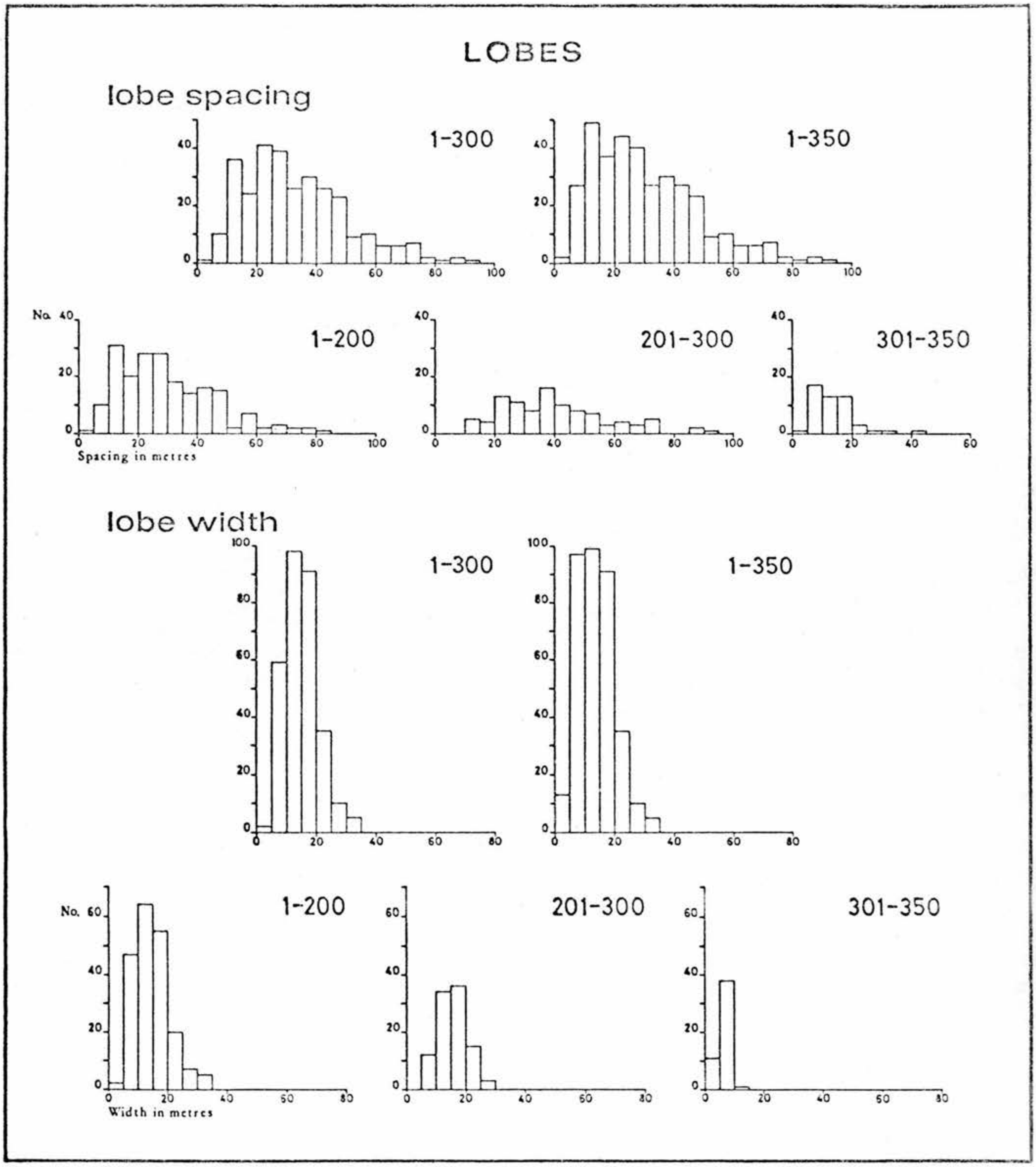

LOBES
lobe spacing
1-300
1-350
1-200
201-300
301-350
No.
Spacing in metres
lobe width
1-300
1-350
1-200
201-300
301-350
No.
Width in metres

Figure 5.10

Stone-fronted lobes between 4 and 30m wide have been reported from Ben Wyvis (Galloway, 1958). The mean width of 100 stone-banked lobes in the Western Cairngorms was, according to King (1968), 13.6m, and the mean of 100 vegetation-covered lobes was 12.8m. Metcalfe (1950), also working in the Cairngorms, observed oval terraces up to 30m wide.

The widths of these features are comparable to the width of solifluction lobes reported from Alaska (Porter, 1966) that ranged from 0.3 to 30m. Larger features up to 30 to 50m across (Price, 1972), or even 100m or more across (Bird, 1974) occur in the Arctic. Turf-banked lobes up to 50m wide occur in the Canadian Rockies (Benedict, 1970). Generally gelifluction or stone-banked lobes are narrower than the larger of the features observed during the present study.

Thus solifluction lobes up to 15 to 20m wide occur in Finnmark (Kallander, 1967) and Greenland (Raup, 1969). Solifluction lobes up to 10m wide have been observed in the Carpathians (Jahn, 1958) and in Scandinavia (Rapp, 1962). Smaller congelifluction lobes and stone garlands up to 2m wide were described by Dutkiewicz (1961, 1967) in Spitsbergen, Sharp (1942) in the Yukon and by Washburn (1967) in Greenland. Even smaller features, up to only 0.3 or 0.6m wide occur in the Southern Uplands of Scotland (Tivy, 1962) and Northern England (Tufnell, 1969).

Lobe Length/Spacing:

The length of a lobe is an extremely difficult parameter to measure, a problem noted by other workers (eg. Kallander, 1967, p.37; Raup, 1969, p.116). This difficulty arises from the fact that the upper part of a lobe usually merges imperceptibly with the slope above, and the exact position at which a lobe form might terminate is usually impossible to perceive. This problem is often made more difficult when closely spaced lobe series are situated in a flight down a hillside. In such a situation only the exposed length of the lobe can be measured, the spacing. This measure refers to the distance upslope between the crest of the riser of one lobe and the base of the riser of the next lobe above. The length and spacing have not been distinguished in the present study; the results only indicate the visible length of lobes in their respective slope situations.

The spacing, or the maximum identifiable length of the granite lobes ranged from 4.3m to 90.4 m (Figure 5.10: 1-300), with a mean of 33.2m (standard deviation 17.4m). About 85% (256) of the granite lobes were less than 50m long, and about 50% (151) were less than 30m long.

Metamorphic lobes ranged from 4.4 to 37.2m long (Figure 5.10:301 -350) with a mean length of 13.8m (standard deviation 6.3m). A majority (62%) were less than 15m long.

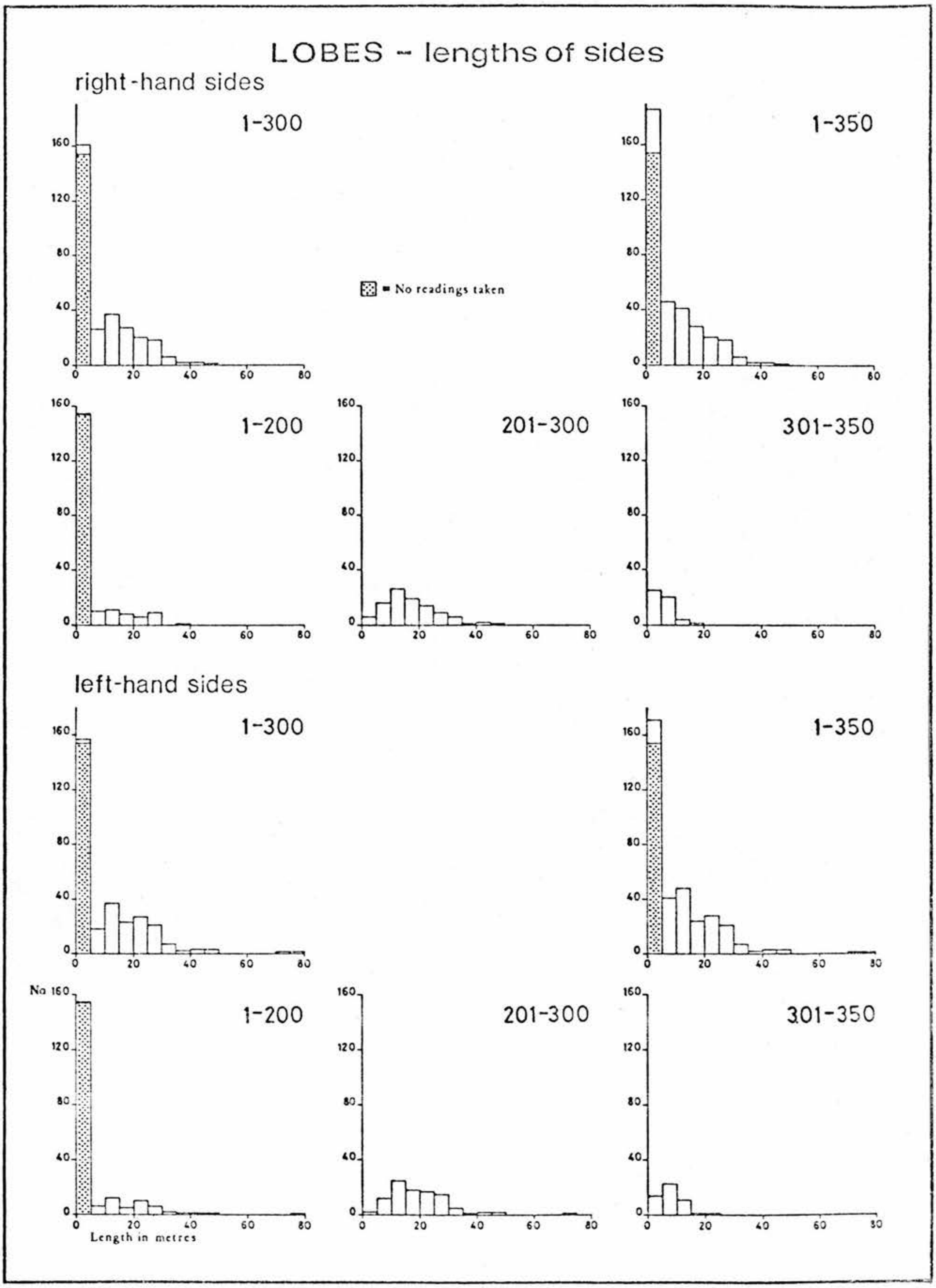
The Lochnagar granite lobes have previously been described as up to 15m or more long (Fyffe, 1968). Stone-banked lobes in the Western Cairngorms were found (King, 1968) to be spaced at 9 to 180m, with a mean spacing of 70m. Individual oval terraces in the Cairngorms have been reported that are up to 30 to 40m long (Metcalfe, 1950).

Ball and Goodier (1970) reported that stone-banked lobes in Snowdonia were some tens of metres in their downslope length. Turfed banked lobes of 10 to 50m long have been observed in Norway (Harris, 1972), and of 3 to 100m long in the Canadian Rockies (Benedict, 1970), and congelifluction lobes up to 30m long in Greenland (Raup,1969). Many smaller lobes exist, such as the 3 to 5m long congelifluction lobes, and the 5 to 7m long sorted congelifluction lobes described by Dutkiewicz (1961) from Spitzbergen, the 7m long garlands described from the Yukon by Sharp (1942) and the 6m long congelifluction lobe examined by Washburn (1967, p.73) in Greenland.

The granite lobes are therefore relatively long features, intermediate in length between the longest turf-banked lobes described and the smaller congelifluction lobes or garlands. They appear to be more closely spaced, downslope, than the Cairngorm examples. The metamorphic lobes are shorter in general than the granite lobes but bigger than many of the arctic examples described.

Length of the Sides:

It became apparent during the examination of lobes in the field that the lobe length or spacing measure did not indicate the total 'free tread length' of the lobe, that is, the length of the lobe-



LOBES - lengths of sides
right-hand sides
1-300
1-350
= No readings taken
1-200
201-300
301-350
left-hand sides
1-300
1-350
1-200
201-300
301-350
No
Length in metres

Figure 5.11

section bordered by side-risers. Thus for the last 146 granite lobes, and all 50 metamorphic lobes the lengths of the two side-risers were measured.

The right-hand and left-hand sides refer to the sides as they appear to the observer when looking up the slope at the frontal riser of the lobe. The lengths of the lobe sides were measured from the crest of the riser to the points on the lobe axis opposite which each terminated (see map Figure 5.12).

The left-hand length of lobe side-risers in the granite area ranged from 2.6m to 76.3m (Figure 5.11: 1-300), with a mean length of 9.7m (standard deviation 12.7m). Of the 146 left-hand sides, 88% (129) were less than 30m long. Right-hand sides ranged from 2.1 to 48.7m (Figure 5.11), with a mean length of 8.3m (standard deviation 10.5m). Of the 146 right-hand sides, 93% (135) were less than 30m long.

In the metamorphic area the left-hand sides of lobes ranged from 1.6m to 20.2m long (Figure 5.11), with a mean length of 7.6m (standard deviation 4.2m). The majority (74%) were less than 10m long. Right-hand sides ranged from 0.9m to 15.9m (Figure 5.11), with a mean length of 5.7m (standard deviation 3.4m). The majority (90%) were less than 10m long.

Thus metamorphic lobes had, in general, a shorter free standing length than granite lobes although the smaller granite lobes fell within the size range of metamorphic lobes. What does appear from both areas is that the left-hand sides of lobes are longer, in their overall size ranges, and the mean lengths of each. These measures do not appear in any reports from other areas, so no other workers have commented upon such a difference. An explanation of this phenomenon was attempted by adopting two approaches. Firstly the possibility that the left-hand side was longer than the right-hand side on all lobes was investigated, and then the two populations were statistically compared. Secondly, the directions of the differences were plotted in their respective aspect quadrants to examine if the different lengths of sides were related to aspect.

The first approach revealed that in the granite area the left-hand side was longer than the right-hand side in 60% (87) of the 146 examples (range 0.2 to 52.3m). In two examples the sides were of equal length, and in the remaining 57 examples the right-hand side was longer (range 0.8 to 27.5m). The differences were statistically compared using the Wilcoxon matched-pairs signed-ranks test (Siegel, 1956, p.p. 75-83). This test utilizes information about the direction and magnitude of the differences within sample pairs. Using this test it was demonstrated that the two lobe sides are significantly different at the 99.9% level. Of the 146 sample pairs, 9 occur in the north-east quadrant, 35 in the south-east, 34 in the south-west and 68 in the north-west. The right-hand side (north-facing) was longer in about 67% (6) of the 9 examples in the north-east quadrant. The right-hand side (north-facing) was longer in only about 51% (18) of the 35 examples in the south-east quadrant. In the south-west quadrant the left-hand side (north-facing) was longer in about 65% (22) of the 34 examples, and the two sides were equal at one example. In the north-west quadrant the left-hand side (north-facing) was longer in about 66% (45) of the 68 cases, and the two sides were equal at one example.

These results suggest that the lobe side that is north-facing most often develops a longer side-riser. In a lobe series, when several lobes occur side by side with their side-risers coalescing upslope the length of each side-riser will be intimately related to the development of each adjacent one. Thus, in a lobe series, if the left-hand side were always, or usually, the longer side in the majority of lobes, then the downslope edge of the lobe series would tend to lie obliquely to the contours, descending farther down the slope as the slope aspect became more southerly. This may be a function of aspect or may only reflect the chance fact that the fronts of a majority of the lobe-series in the granite study area (60% of the lobes measured) lie obliquely to the slope in the right hand direction, that is the lobe fronts descend in a line towards the observer's right-hand when looking up the hill, in the western sector, and decline to the left-hand in the eastern sector.

In the metamorphic area the left-hand lobe side-riser was longer than the right-hand in 62% of the examples, and the right-hand side the longer in 38%. The two lobe side population pairs are statistically distinct at the 99.9% confidence level (Wilcoxon matched-pairs signed-ranks test).

Of the 50 examples, 11 occur in the north-east quadrant, 29 in the south-east, 4 in the south-west and 6 in the north-west. In the north-east quadrant the left-hand sides (south-facing) were longer in 73% (8) of the 11 examples. In the south-east quadrant the left-hand (south-facing) side was longer in 59% (17) of the 29 examples. Of the four lobes in the south-west quadrant, the left-hand side was longer at two examples, and the right-hand side at two examples. Of the 6 examples in the north-west quadrant the left-hand (north-facing) side was longest at 4 examples.

The results from the metamorphic area suggest that the apparent pattern of differences between the lobe sides observed in the granite area does not apply to this area. It is concluded that the differences in sides occur as a result of the development of the fronts of lobe-series obliquely to the contours. Also, any apparent preference for a certain side to be longer than the other in a particular quadrant reflects only the predominance of right-hand or left-hand oblique fronts in that area, developed due to peculiarities of the terrain rather than the direct affects of aspect exposure.

Lithology:

Lobes were abundantly developed upon the granite rocks of the Lochnagar and Mount Keen Massifs. They were also developed upon the quartzite rocks of the metamorphic area, but were not observed upon the adjacent schists and meta-sediments.

The lithology of the bedrock imparts distinctive characteristics to the lobes in the two parts of the study area. In the granite area the debris was coarse, blocky or platy with rounded edges, and supported thick crusts of lichens, In the quartzite area the debris was smaller, more rubbly than bouldery, generally blocky but with sharp and irregular edges and supported little lichen growth. Corresponding with the differences in debris size, the granite lobes were usually larger than the quartzite lobes. Heather and rhacomitrium were the dominant vegetation types upon the treads of granite lobes, whereas vaccinium with some heather grew upon the treads of the quartzite lobes. In both areas the risers were usually vegetation free. The treads had accumulations of peat supporting the vegetation, whereas the risers appeared to be too

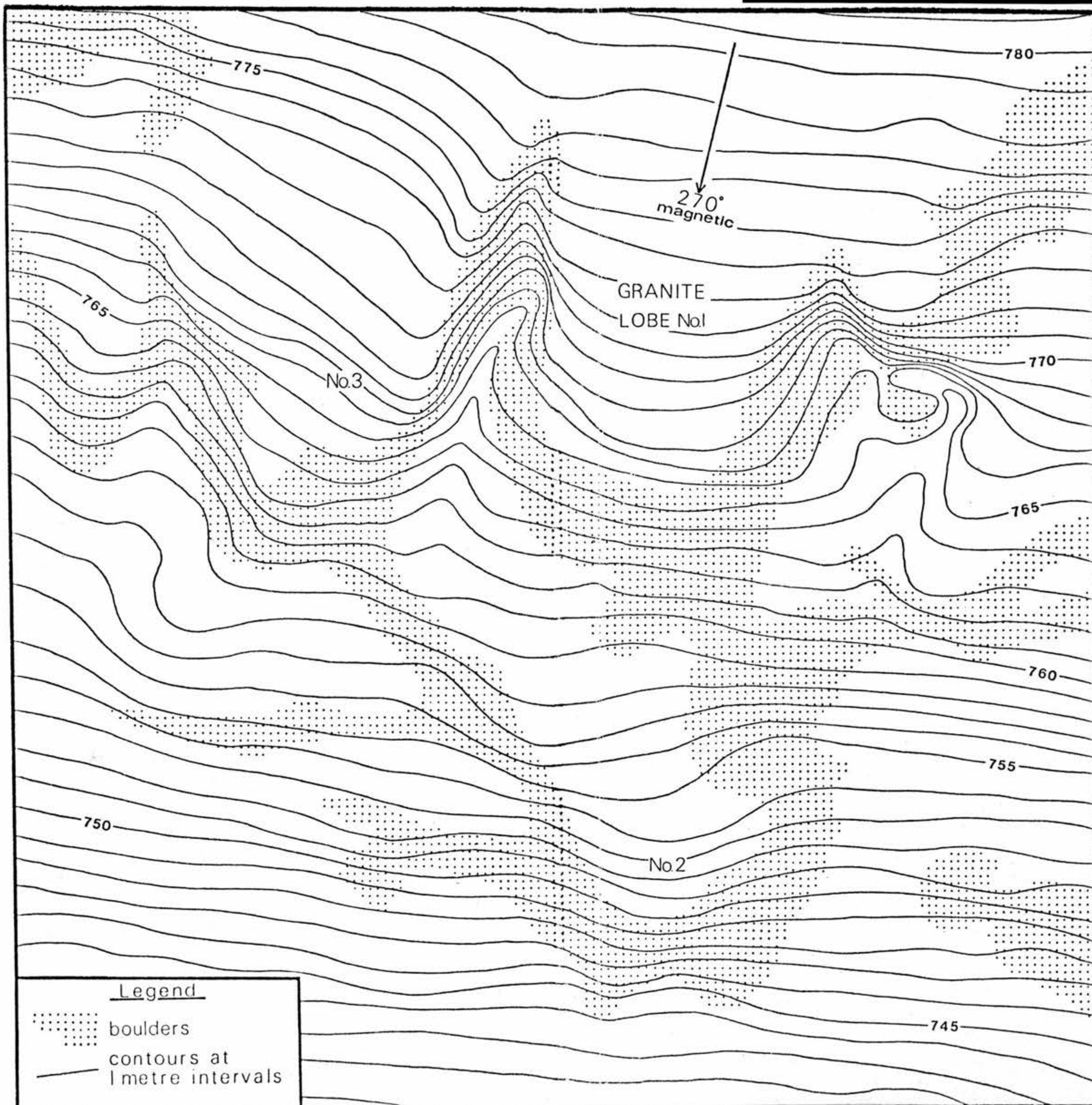


Figure 5.12 Plane table survey map of a complex of boulder risers in granite rocks. The site occurs upon the west-facing slopes of Meal an Tionail, Lochnagar. Three lobes are delimited, as shown by the contours, but many irregular and incomplete risers are present illustrating the problem of recognising lobes in the field.

steep, and open between the debris.

Slopes upon which lobes occurred appeared to be steeper in the metamorphic area; thus the facets of metamorphic lobes were generally steeper than those of granite lobes.

The Relationship between the Angular Facets of Lobes

The angles of the various facets of lobes have been described in the preceding sections, and it has been shown that much variation occurs within each facet between different lobes and especially between the granite and the metamorphic areas. The relationships between the gradients of the separate lobe facets has not been considered, or their relationship to the slope angle.

The Angle Below:

It was pointed out in the Angle Below section, that this facet was usually less steep than the overall slope angle. In the granite area the slope angle ranged from 10° to 34° (mean 20°) and the angle below from 5° to 32°. Examination of the data (Appendix 1) reveals that the slope angle was steeper than the angle below in 78% (234) cases and equal to the angle below in about 10% (29) of cases. Thus in only 12% of the examples was the angle below the riser of a lobe steeper than the overall slope angle. This suggests that lobes in the granite area tend to terminate at slight breaks in the general slope gradient. The angle below was less than the slope gradient by between 1° and 15° (mean 3.8°), but only exceeded the slope angle by between 1° and 6° (mean 1.8°).

A similar relationship held in the metamorphic area where 64% of the lobes terminated on slopes with a lower gradient than the overall slope angle. The angle below 8% of the lobes was equal to the overall slope angle, and the angle below was steeper in the remaining 28% of examples. Ground below the risers of metamorphic lobes was less steep than the slope angle by from 1° to 15° (mean 6.1°), and was steeper by from 1° to 5° (mean 3.0°).

The riser angle was, inevitably, always steeper than the angle below. It is this difference that causes the riser, and lobe front, to be defined. In the granite area the riser angle was between 2° and 32° steeper than the angle below (mean 11.6°). Risers in the metamorphic area were between 5° and 28° steeper than the angle below (mean 12.8°).

The surface angle of the treads of the lobes, at the steeper frontal part, was usually steeper than the angle below. In the granite area the surface angle was steeper than the angle below in 70% (211) of the cases, ranging from 1^{o} to 13^{o} (mean 4.5^{o}). The surface angle sloped at the same gradient as the angle below in 9% (26) of the examples. Lobes had surface angles less steep than the angle below in 21% (63) cases, ranging from 1^{o} to 7^{o} (mean 2.4^{o}). Such a distinction was less marked in the metamorphic area where only 56% of the lobes had surface angles steeper than the angle below (range 1^{o} to 12^{o}: mean 4.6^{o}). Only 2% of the surface angles were equal in gradient to the angle below, and 42% were less steep (range 1^{o} to 7^{o}: mean 2.7^{o}).

The Riser Angle:

It has been shown in the preceding section that the riser angle of lobes was always found to be steeper than the angle of the ground in front of the lobe. In contrast the angle of the riser, measured at the front of the lobe, was not always steeper than the surface angle of the tread.

In the granite area the riser angle was found to be equal to the surface angle in 1% (3) of the examples, and steeper than the surface angle in 98% (293) of the examples (range 1^{o} to 28^{o}: mean 9.1^{o}). In the remaining 1% (4) of the lobes the riser angle was less steep than the surface angle (range 1^{o} to 5^{o}: mean 2.8^{o}). The apparent anomaly can be explained by the fact that riser angle was measured at the front of the lobe, and not the sides of the lobe. Thus the side-risers were always steep and well defined but at the front of four granite lobes the debris spilled out as an apron, rather than piling up as a steep frontal bank. Similarly in the three examples where the riser angle sloped at the same angle as the surface, the front of the lobe had run forward rather than piling up as a bank. Risers in the metamorphic area were always steeper than the angle of the lobe surface, ranging from 3^{o} to 27^{o} steeper (mean 11.4^{o}).

Part 1: Summary and Conclusions

The Distribution of Lobes

Lobes were found at altitudes between 580m to 1110m a.s.l. in the south-east Grampian study area. The upper limit to lobe development was determined by the available relief in the area. Lobes occurred down to near the bases of the hills investigated in the granite parts of the study area (640m), but terminated about mid-slope on the hills in the metamorphic area (580m). It appears that lobes have not developed below about 600m in the area.

Aspect does not exert a dominant control over the development of lobes. Examples were found upon slopes of all aspects, except between 357° and 011°. It is suggested that lobes probably never developed upon slopes with this aspect in the present study area, due to the lack of freeze-thaw activity on north-facing slopes. Granite lobes appeared to favour slopes with a westerly aspect. This distribution was shown statistically (Kolmogorov-Smirnov) to be different from the distribution of slopes within the sampling areas; thus it is suggested that the development of the granite lobes was favoured upon west-facing slopes. Metamorphic lobes appear to favour south-east facing slopes.

Granite lobes were developed upon slopes between 10° and 34° (mean 20.0°) and metamorphic lobes upon slopes between 18° and 33° (mean 24.4°). A random sample of slope angles within the study area was shown to be statistically distinct from the lobe-slope sample. Thus it is concluded that slopes between 10° and 34° favour the development of the lobe types examined.

Vegetation growing upon the slope is independent of the development of the lobes and post-dates them. The treads are well vegetated but the risers are usually unvegetated.

The Characteristics of Lobes

Lobes were examined in relation to the characteristics of their riser and their tread.

Granite lobes had risers at angles from 15° to 45°, from 2.0m to 28.4m long and between 0.3m and 5.9m high. The angle of the ground below the riser ranged from 5° to 32° and was usually less (in 78% of cases) than the overall slope angle. Thus it is suggested that lobes tend to terminate at breaks in the overall slope gradient.

Metamorphic lobes had risers of from 22° to 54° gradient, between 0.6m and 7.0m long, and between 0.2 and 1.3m high. The angle of the ground below the riser ranged from 11° to 34°, and was less steep than the overall slope in 64% of the examples.

The treads of granite lobes declined at gradients between 9° and 36°, were between 3.9m and 33.3m wide and extended for between 4.3m and 90.4m from the riser crest to the base of the riser of the next lobe above. The left-hand side risers were between 2.6m and 76.3m long and the right-hand side risers between 2.1m and 48.7m. It is suggested that the different lengths of the two sides reflect the irregular development of lobe series, whose fronts often lie obliquely to the contours.

Metamorphic lobes had treads sloping between 15° and 32°, and from 3.9m to 10.4m wide. The lobes ranged between 4.4m and 37.2m long. Left-hand side risers were from 1.6m to 20.2m long, and right-hand side risers from 0.9m to 15.9m long.

Part 2: The Nature of the Boulder Lobes

Introduction

Four approaches were adopted in an attempt to investigate the nature of the boulder lobes developed in the study area.

Initially, trenches were dug into the treads, along the axial-line, of five lobes in the granite area but these studies had to be discontinued because of the high boulder content of the centres of the lobes. Nevertheless, the results of these investigations are reported as they shed valuable light upon the nature of these features. Analyses of boulder size were carried out to determine the average, and range of, sizes making up different portions of the lobes. The shape and packing of the boulders were visually assessed and described. Finally the fabric of the borders was investigated by conducting stone orientation studies upon twelve granite lobes and four metamorphic lobes.

Trench Studies:

Several authors have investigated the internal composition and structure of gelifluction sheets (eg. Tivy, 1962; Ragg and Bibby, 1966; Everett, 1967) and lobes or terraces (eg. Watt and Jones, 1948; Benedict, 1966, 1970; Jahn, 1967, p.213; Kallander, 1967, p.38) by digging trenches, or in stream or gully exposures (eg. Watson, 1969a; White and Mottershead, 1972).

A similar approach was attempted in the present study.

No natural sections were found through any of the lobes; therefore short pits were dug into the tread, along the axial-line, of five lobes in the granite area. These lobes were situated upon the slopes of Meall an Tionail (Lobe 8), Cnapan Nathraichean (Lobe 83), Cuidhe Crom (Lobe 103), and the summit col (Lobe 171) of the Lochnagar area, and Gathering Cairn (Lobe 202) from the Mount Keen area. In all five lobes a similar situation was encountered. A layer of peat up to 1.2m thick (Lobe 202) was developed upon a mass of boulders without visible interstitial fines. The peat layer was supported across the gaps between the boulders by the partly decayed stems of the woody moorland plants.

The profile of the pit into the tread of Lobe 103 is described here to illustrate a typical sequence. This pit was situated upon the axis of the lobe, 16m from each of the sides (lobe 32.2m wide), and 9.5m upslope from the crest of the riser (lobe 21.0m long; the lengths of the sides were not measured). The pit was situated at the point where the steeply convex profile of the front began to shallow. The tread was vegetated with an assemblage consisting dominantly of heather (Calluna vulgaris) and some rhacomitrium and grasses.

Below the vegetation layer the pit revealed a moist, but crumbly dark black peat. At 25cm from the surface the peat became more moist and compact, producing shiny faces when cut. At 34cm granite fragments appeared in the peat, with flakes of granite and sand grains. At 69cm the first solid granite boulder appeared, with a sub-rounded shape, a wet surface and a well-weathered flaking shell. The boulder was very orange in colour, in contrast to the almost white appearance of the boulders in the riser. At this level the peat contained an orange, sandy material, which was presumed to be the weathering product of the granite. At 88cm this layer was penetrated and below this boulders occurred with no interstitial filling in evidence. Material in the pit fell through the gaps between the boulders. Excavation had to be discontinued at this depth as the boulders were too large to be lifted.

A short trench cut into the tread of a metamorphic lobe (Lobe 348) showed a similar situation occurring in this area. Peat on the riser tread was up to about 45cm thick, and supported a vegetation consisting predominantly of heather. Below the peat layer was an openwork rubble of quartzite boulders of similar dimensions to those composing the riser.

It is concluded from the limited number of excavations performed that the lobes examined in this study appear to differ from the majority of lobe-types previously described in that they do not have a central zone composed of fine material. In consequence they cannot be termed stone-banked lobes, in the sense of sorted steps (Washburn, 1956, p.833), or in the sense of stone-banked lobes as accepted by Benedict (1970, p.176); "lobate masses of rocky debris underlain by relatively stone-free, fine-textured, moving soil" (see Chapter 4), unless fine material does occur at depth. The interior is not composed of material capable of saturated flow, and there is no evidence of similar material at a shallow depth. These features are similar to those described by Lundquist (1962,p.53) occurring in areas with extremely high boulder content. The features were formed of masses of pure boulder material, consisting of boulders and stones without fines. Such features he termed boulder-steps.

Galloway (1958, p.132) recognised that the material forming the stone-fronted lobes on Lochnagar was overwhelmingly large blocks of granite with only a scanty matrix of coarse granitic sand. A similar conclusion was reached by Grant (1971, p.39) who nevertheless referred to them as stone-banked lobes. Fyffe (1968) believed the Lochnagar lobes to be mainly stone-fronted with fine material behind the front wall.

In the Cairngorms Watt and Jones (1948) dug pits into the platforms of boulder-banked terraces in the Cairngorms to reveal a buried soil surface, or surfaces, overlain by sandy, gravelly deposits. Metcalfe (1950) examined 'oval terraces' in the Cairngorms, which were banked up with closely packed boulders whose interstices were packed with smaller rubble and gravel and the whole covered with peat. Soil on the surface was found to have a consolidated boulder rubble at the base covered with gravel. Granular peat covered most of the platform. King (1972,p.155) determined that the interior of stone-banked lobes in the Western

Cairngorms consisted of boulders, soil and vegetation. Sugden (1970a) also believed that stone-banked lobes in the Cairngorms had risers of stones and treads of finer material.

Ball and Goodier (1970, p.202) found lobes in Snowdonia with a very high stone content that they suggested were almost pure stone lobes rather than simply stone-banked lobes. Benedict (1970, p.176) reported stone-banked lobes in the Canadian Rockies with treads that were composed of boulders and stones without visible fine material.

Thus it appears that the lobes described are not unique in having treads composed of boulders devoid of any fine material. What does appear to be unusual is the large size of the boulders in many of the present granite lobes.

The mean diameter of boulders found in King's (1972) Cairngorm lobes was 23.0cm (32.5cm mean in the frone riser), and 20cm to 50cm maximum dimension in Benedict's (1970) Rocky Mountain lobes. The mean diameter of boulders in the present granite lobes was usually over 65cm.

Boulder Size Studies:

In order to present some quantitative indication of the size ~~of the size~~ of the boulders making up the granite and metamorphic lobes the dimensions of the boulders (samples of 50 boulders) in the risers of eight granite lobes (Lobes 108, 127, 164, 171, 192, 202: Photograph 5.3, 224, 235) and four metamorphic lobes (Lobes 317, 337, 348: Photograph 5.7, 350: Photograph 5.8) were measured. The results are presented in Table 5.B. Samples were taken from the front, and two side risers of each lobe (see Boulder Fabric section for the sampling procedure).

Granite Lobes:

Boulders forming lobes in the granite areas range from an average of 18.6cm (top front of Lobe 127) to 137.1cm (front of Lobe 164) in their longest dimension. The largest boulder measured was in the front of Lobe 164 (adjacent to Lobe 163 in Photograph 5.5), situated in the summit col of Lochnagar, and was over 4m long (420cm). King (1968, p.98) observed boulders up to 1m average diameter in garlands, and Sugden (1970a) reported boulders up to 1.5m diameter, in stone-banked lobes in the Cairngorms.

There is no evidence that on average the largest boulders occur in the fronts of lobes except perhaps in lobes 164 and 192 (Table 5.B) and in the basal section of the front riser of lobe 127. No samples were measured in the centres of the lobes due to the difficulty of access through the peat cover, but the trenching studies suggest that the size of boulders in the centres is similar to those of the risers. Thus, there was no indication of any sorting of large boulders to form the risers.

The possibility of a change in boulder size with increasing distance downslope was investigated on two slopes. Lobe 164 occurs downslope of Lobe 171 in the summit col of Lochnagar, and Lobe 224 occurs downslope of Lobe 235 on the slopes of Gathering Cairn of the Mount Keen granite area. The average boulder in Lobe 164 (average boulder length 125.8cm) is rather larger than the average boulder in Lobe 171 (average boulder length 93.1cm), situated 190m upslope from Lobe 164. Conversely, the average boulder in Lobe 224 (65.3cm) is smaller than the average boulder in Lobe 235 (78.7cm). The former situation suggests that the largest material has moved farther downhill that the smaller (of Lobe 171). It could equally be that the material of Lobe 164 is locally derived, as it is evident from the numerous granite slabs and outcrops in the summit col that the bedrock is not far below the surface. The latter situation suggests that the granite boulders were originally derived from the summit areas and became progressively reduced in size with distance downslope (c.f. Eakin, 1916), but the information available is not sufficient to allow any definite conclusions to be drawn.

The front riser of Lobe 127 was interesting in that it appeared to comprise two sections, an upper zone composed of finer debris and a lower zone or 'apron' of coarser blocks. Separate samples (of 50 boulders each) from the top and bottom sections revealed that the average size of boulders in the upper section was 18.6cm, and in the lower section 26.2cm. It is possible that this lobe was composed almost entirely of the finer 'rubble' from which the larger blocks had been sorted during

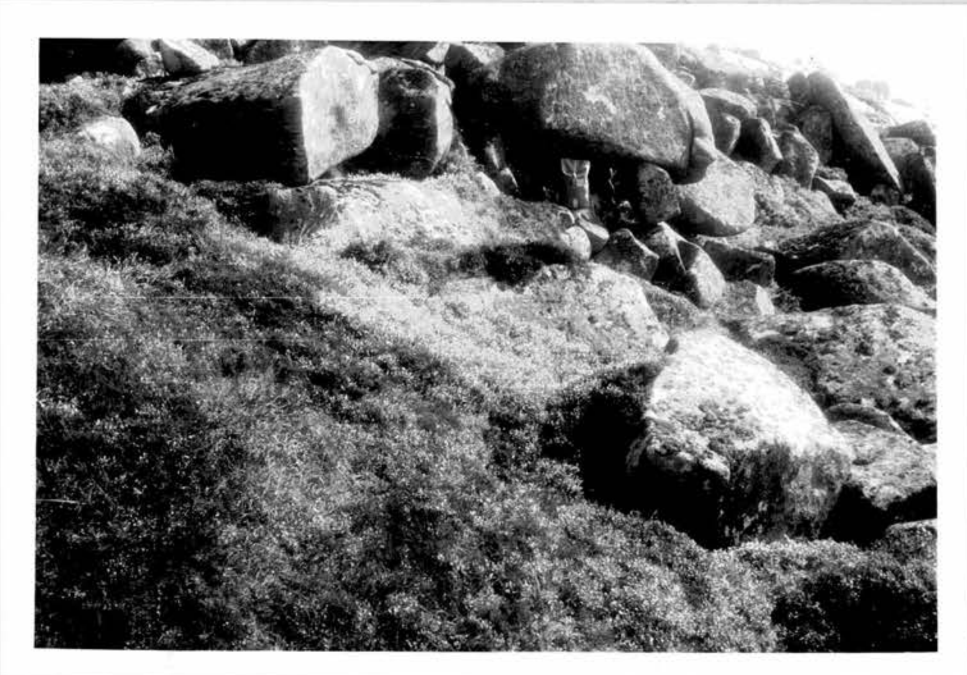
TABLE 5.B

The Average Size of Boulders in Sample Lobes

GRANITE LOBES

		Average Length (cm)	Overall average (cm)
Lobe 108	Front	68.6	
	R.H.Side	69.4	71.4
	L.H.Side	76.3	
Lobe 127	Front Top	18.6	
	Base	26.2	22.5
	R.H.Side	22.5	
	L.H.Side	22.7	
Lobe 164	Front	137.1	
	R.H.Side	122.2	125.8
	L.H.Side	117.9	
Lobe 171	Front	79.9	
	R.H.Side	104.3	93.1
	L.H.Side	95.0	
Lobe 192	Front	82.5	
	R.H.Side	68.8	77.1
	L.H.Side	79.9	
Lobe 202	Front	78.2	
	R.H.Side	67.8	79.2
	L.H.Side	91.7	
Lobe 224	Front	64.0	
	R.H.Side	68.7	65.3
	L.H.Side	63.2	
Lobe 235	Front	77.0	
	R.H.Side	84.7	78.7
	L.H.Side	74.3	

PHOTOGRAPH 5.5 The steeply piled stones of the riser-front of Lobe 163, the lowest lobe in the summit col of Lochnagar, above the Stuic Corrie (shown in Photograph 5.2).



PHOTOGRAPH 5.6 The seemingly precariously balanced granite boulders of the riser of Lobe 183, above the Dubh Loch. The rucksack is 45cm high.

TABLE 5.B

The Average Size of Boulders in Sample Lobes

METAMORPHIC LOBES

		Average Length (cm)	Overall average (cm)
Lobe 317	Front	36.4	
	R.H.Side	42.0	36.1
	L.H.Side	30.0	
Lobe 337	Front	28.5	
	R.H.Side	33.2	33.3
	L.H.Side	38.1	
Lobe 348	Front	29.4	
	R.H.Side	31.5	31.2
	L.H.Side	32.6	
Lobe 350	Front	19.4	
	R.H.Side	21.1	21.1
	L.H.Side	22.8	

PHOTOGRAPH 5.7 Quartzite lobes on the south-facing slopes of Creag nan Gabhar. Lobe 348 is in the foreground.

PHOTOGRAPH 5.8 Quartzite Lobe 350 on the south-facing slopes on Creag nan Gabhar. The rucksack is 45cm high.

movement of the lobe. Upon emergence at the front they would presumably roll to the base.

Metamorphic Lobes:

Boulders sampled in the metamorphic lobes were generally smaller than those in granite lobes, except in granite lobe 127 (compare Photographs 5.6 and 5.8). The average boulder length ranges from a minimum of 21.1cm (right-hand side of lobe 350) to a maximum of 42.0cm (right-hand side of lobe 317), about one third of the average length of boulders from the front of granite lobe 164. Again there is no general indication of any size sorting between the fronts and sides except perhaps a slight decrease in size towards the front (Lobes 337, 348, 350) (Table 5.B).

Boulder Shape and Packing:

The boulder risers in both the granite and metamorphic areas showed no evidence of any imbrication or preferred dip direction, only a general tendency to be oriented tangentially to the edges of the lobe (see the Fabric Section). The large size of the boulders and the lack of interstitial fines gave the risers a very open appearance, with the boulders seemingly in a chaotic jumble (Photographs 5.4 and 5.7), often perched in, what appeared to be, unstable positions (Photographs 5.5 and 5.6).

Granite boulders were generally 'blocky' in shape (Photographs 5.4, 5.6 and 5.7), that is short rectangular prisms. Some were platy (Photographs 5.3 and 5.5). The long axes of platy fragments usually appeared to be aligned at a tangent to the lobe edge, with the intermediate (b-axis) dipping into or out-of the lobe. To understand effectively the dip characteristics of the boulders it is misleading to consider only the plunge of the long-axis as was done in the present study, from which no preferred pattern emerged (Figure 5.13).

Risers in the metamorphic area, composed of smaller blocks, appeared to be more compact (Photographs 5.7 and 5.8) but only due to the smaller interstices. They lacked fines in the risers so the structure of the risers was very open. The blocks were usually rectangular prismatic but many had jagged and irregular edges and faces, in contrast to the granite blocks that usually

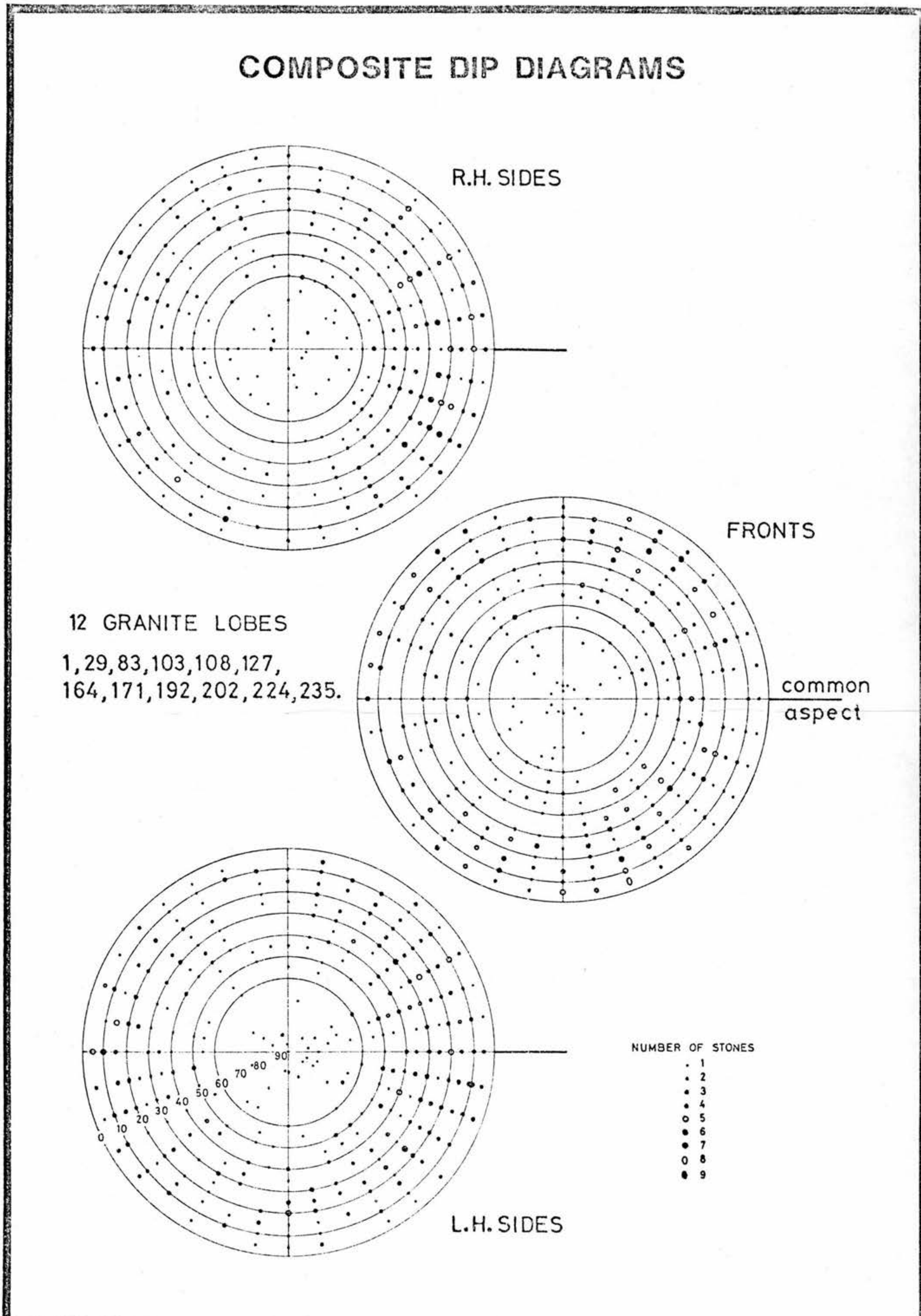

COMPOSITE DIP DIAGRAMS
R.H. SIDES
FRONTS
12 GRANITE LOBES
1, 29, 83, 103, 108, 127,
164, 171, 192, 202, 224, 235.
common
aspect
90
80
70
60
50
40
30
20
10
0
NUMBER OF STONES
1
2
3
4
5
6
7
8
9
L.H. SIDES

Figure 5.13a

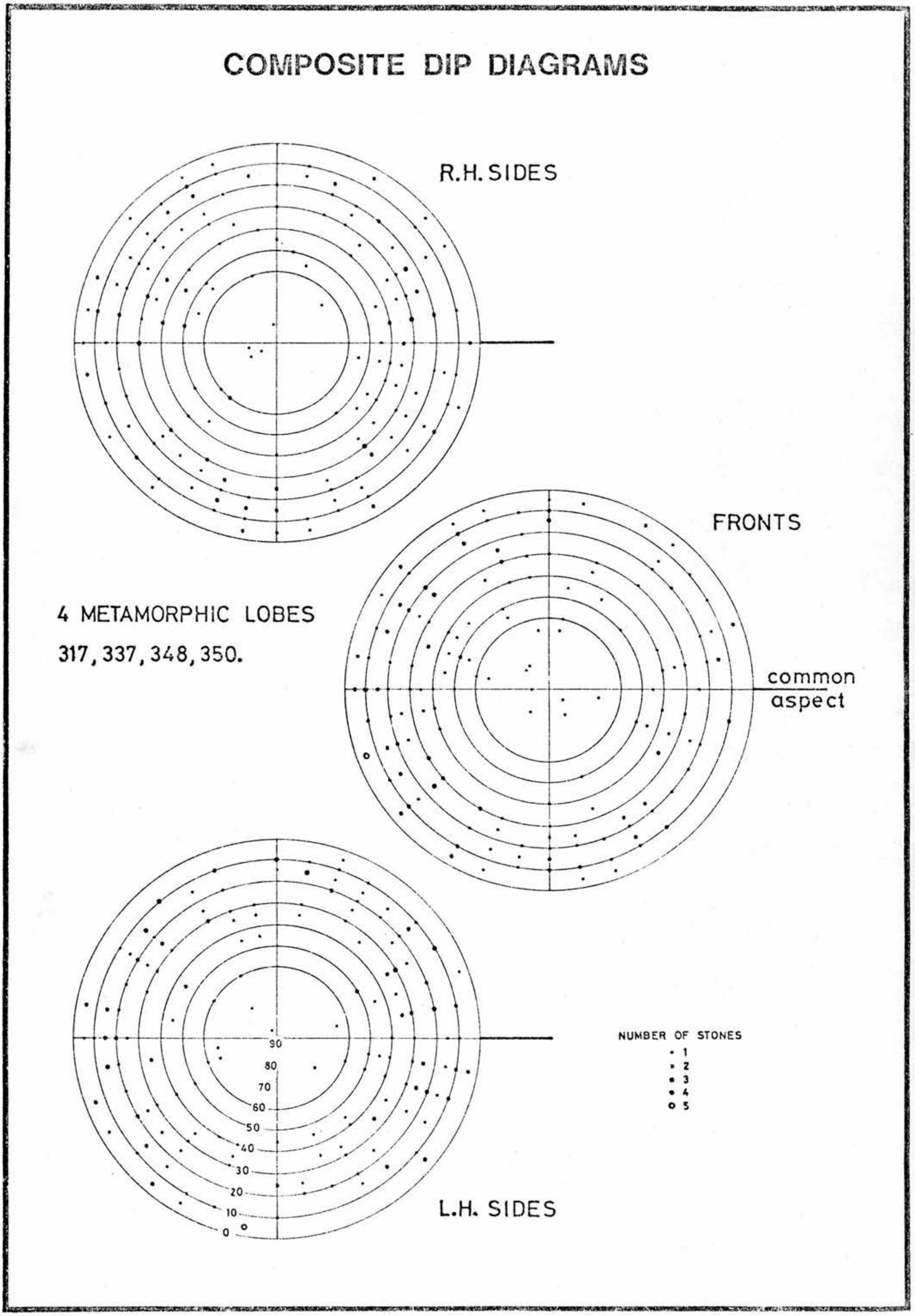

COMPOSITE DIP DIAGRAMS
R.H. SIDES
FRONTS
common aspect
4 METAMORPHIC LOBES
317, 337, 348, 350.
L.H. SIDES
NUMBER OF STONES
1
2
3
4
5
90
80
70
60
50
40
30
20
10
0

Figure 5.13b

had rounded edges, although the blocks were subangular to subrounded (Photographs 5.3 and 5.4).

Boulder Fabric:

The fabric of a deposit is the orientation, or lack of it, of the elements of which the deposit is composed. If a significant number of the constituent elements have assumed a certain orientation in preference to all others these elements are said to show a preferred orientation or anisotropic fabric (Pettijohn, 1957).

Investigations of the fabrics of periglacial slope deposits, in the form of uniform gelifluction sheets or head deposits, have shown that the long axes of contained stones generally tend to be oriented parallel to the direction of movement, that is approximately normal to the slope contours (eg. Fitzpatrick, 1958, 1975; Kozanski, 1961; Rapp and Rudberg, 1960; Rudberg, 1962; Tivy, 1962; Ragg and Bibby, 1966; Kirby, 1967; Watson and Watson, 1967; Watson, 1969a, 1969b; Washburn, 1973). When movement of the layer ceases, such as at the edge of a lobe or terrace, the stones are often re-oriented to a position at right angles to the previous movement direction, tangential to the edges of the lobe or terrace (eg. Lundqvist, 1949, 1962; Benedict, 1966, 1970). This re-orientation does not always occur, however. Many authors have determined that a downslope orientation, or an orientation pattern diverging outwards from the axis of the lobe towards the curved edges, persists even in the borders of these features, be they stone-banked or earth lobes (eg. Rudberg, 1958; Pissart, 1963b; Kallander, 1967; King, 1972, p.p. 161-162; White and Mottershead, 1972; Archer et al., 1973). Stone orientation studies within the centres of lobes have usually revealed a preferred orientation parallel to the direction of movement (eg. Lundqvist, 1949, 1962; Rapp and Rudberg, 1960; Benedict, 1970)

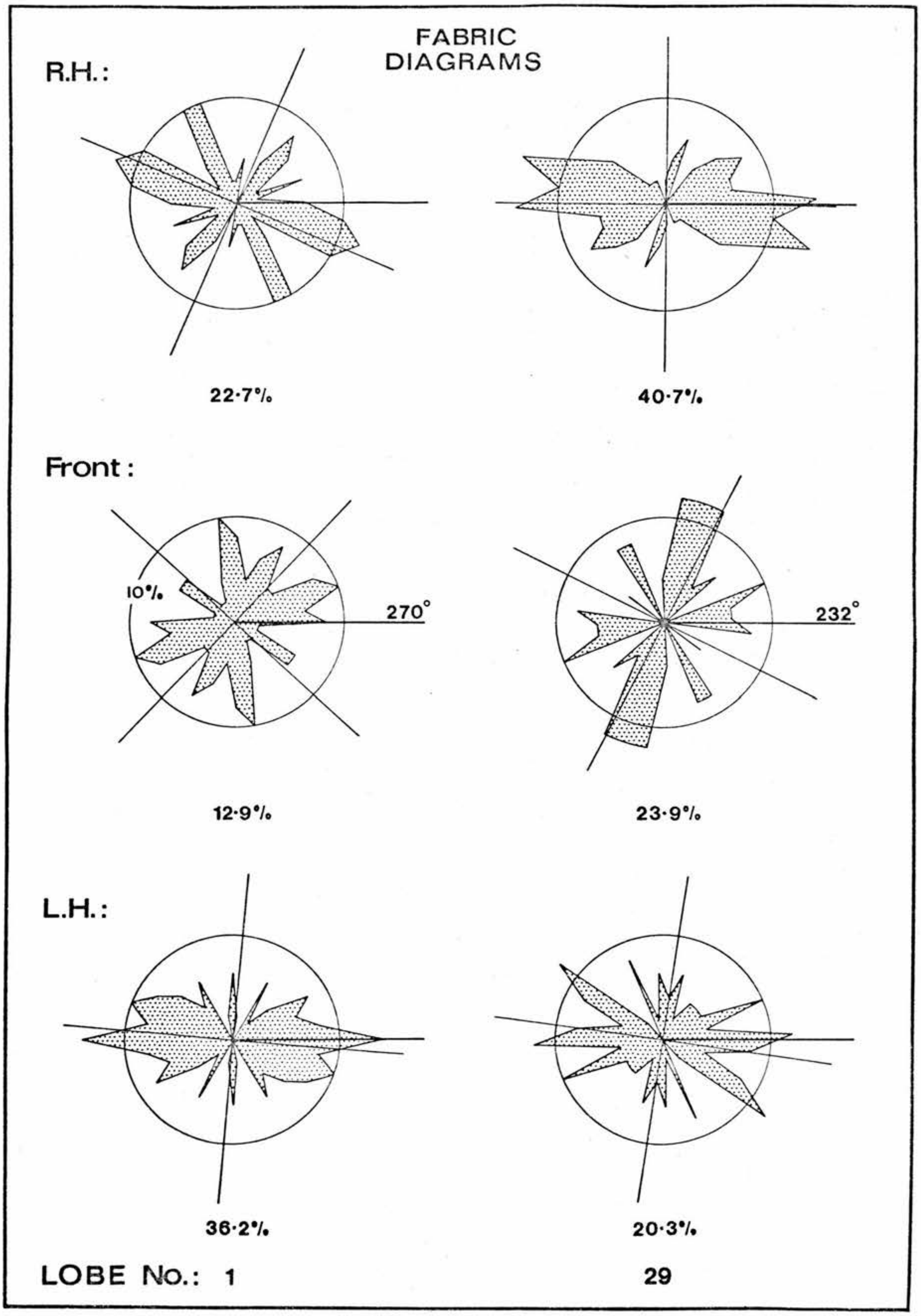
Previous studies have largely been concerned with fine-grained deposits containing large fragments dispersed throughout, or with the fine rubbly debris of small stone-banked lobes. Few studies have considered the possibility of fabric patterns being developed in features containing such large boulders, except perhaps in studies of blockfields (eg. Caine, 1968, 1969b, 1972). The present study sought to determine if such large boulders, without a surrounding medium capable of true gelifluai saturated flow, would show any detectable fabric patterns.

The unvegetated boulder risers of twelve granite lobes and four metamorphic lobes were analysed. Three separate samples were taken, one from each of the front, the right-hand, and the left-hand risers. For the purposes of sampling, the riser front was arbitrarily defined as terminating upslope at a line visualised across the crest of the riser, orthogonal to the lobe axis. Each sample consisted of 50 boulders, this number being considered a sufficiently large sample to reveal any fabric pattern present (Young, 1969).

Sampling was carried out by traversing the riser, and taking readings from every third boulder encountered. A return traverse was made parallel to the first and so on until the total was reached. Only particles with a length to breadth ratio greater than 3:2 were measured, this being generally accepted as the minimum elongation for fabric studies (Young, 1969, p.2345; King, 1972, p.161). The alignment of the long axis of each boulder was measured using a Silva compass.

The orientation results were plotted upon polar equidistant projections in 10° categories (Figures 5.14 to 5.21), upon which orientation with respect to magnetic north is represented by the circumferential scale, and the number of observations by the radial scale. Plots were made in the eastern-sector and duplicated in the western-sector to produce a symmetrical rose. The resulting orientation diagrams have been standardised to show the downslope direction to the right-hand side of the page, marked with the slope aspect in degrees magnetic, and the right-hand and left-hand side roses placed in their correct relative positions.

Vector analysis was used to determine a value for the preferred orientation direction, and the strength of this value in percentages (Krumbein, 1939; Curray, 1956). The calculated vector direction gives a measure of the central tendency of the



FABRIC DIAGRAMS
R.H.:
22·7%
40·7%
Front:
10%
270°
232°
12·9%
23·9%
L.H.:
36·2%
20·3%
LOBE No.: 1
29

Figure 5.14

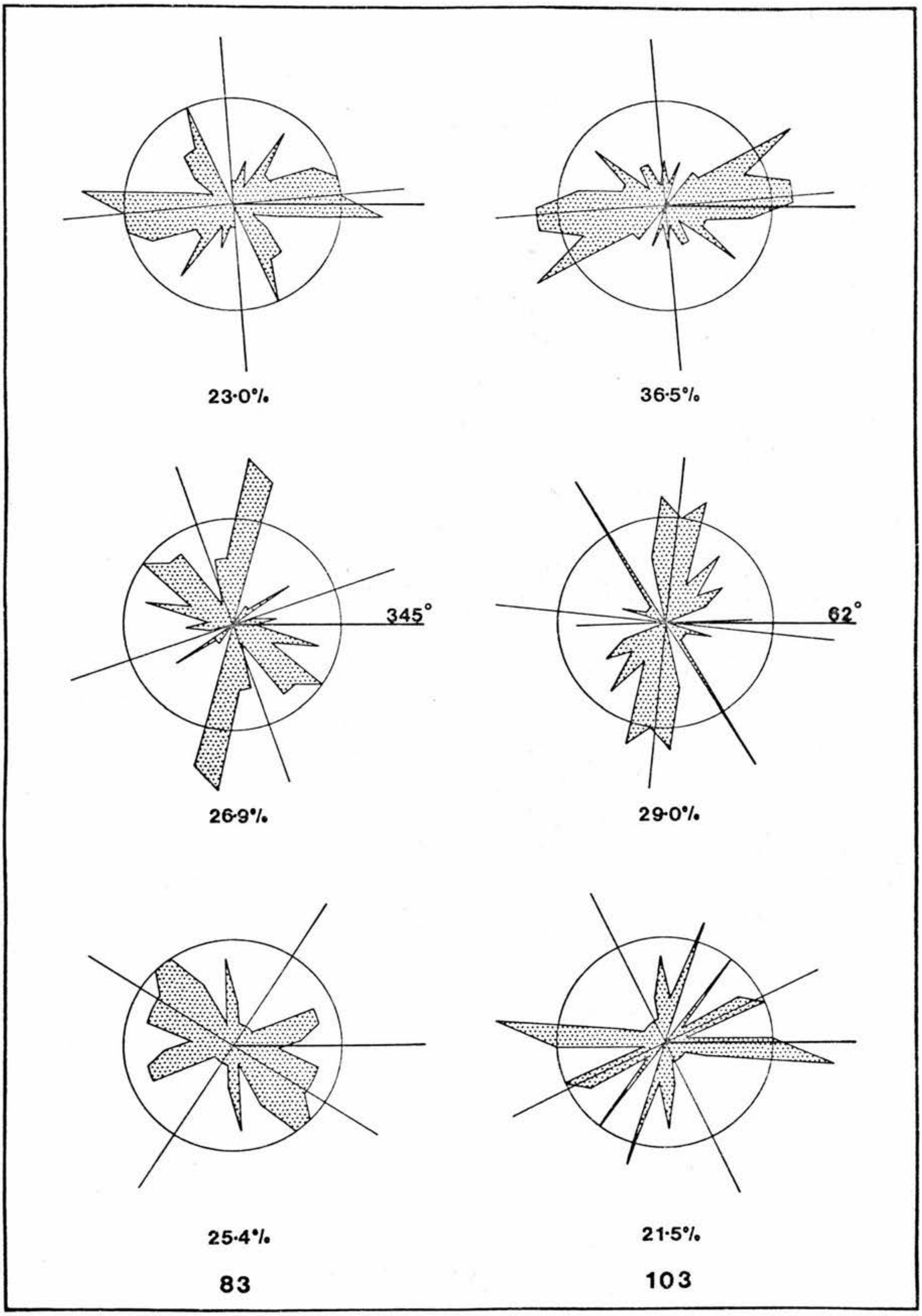


Figure 5.15

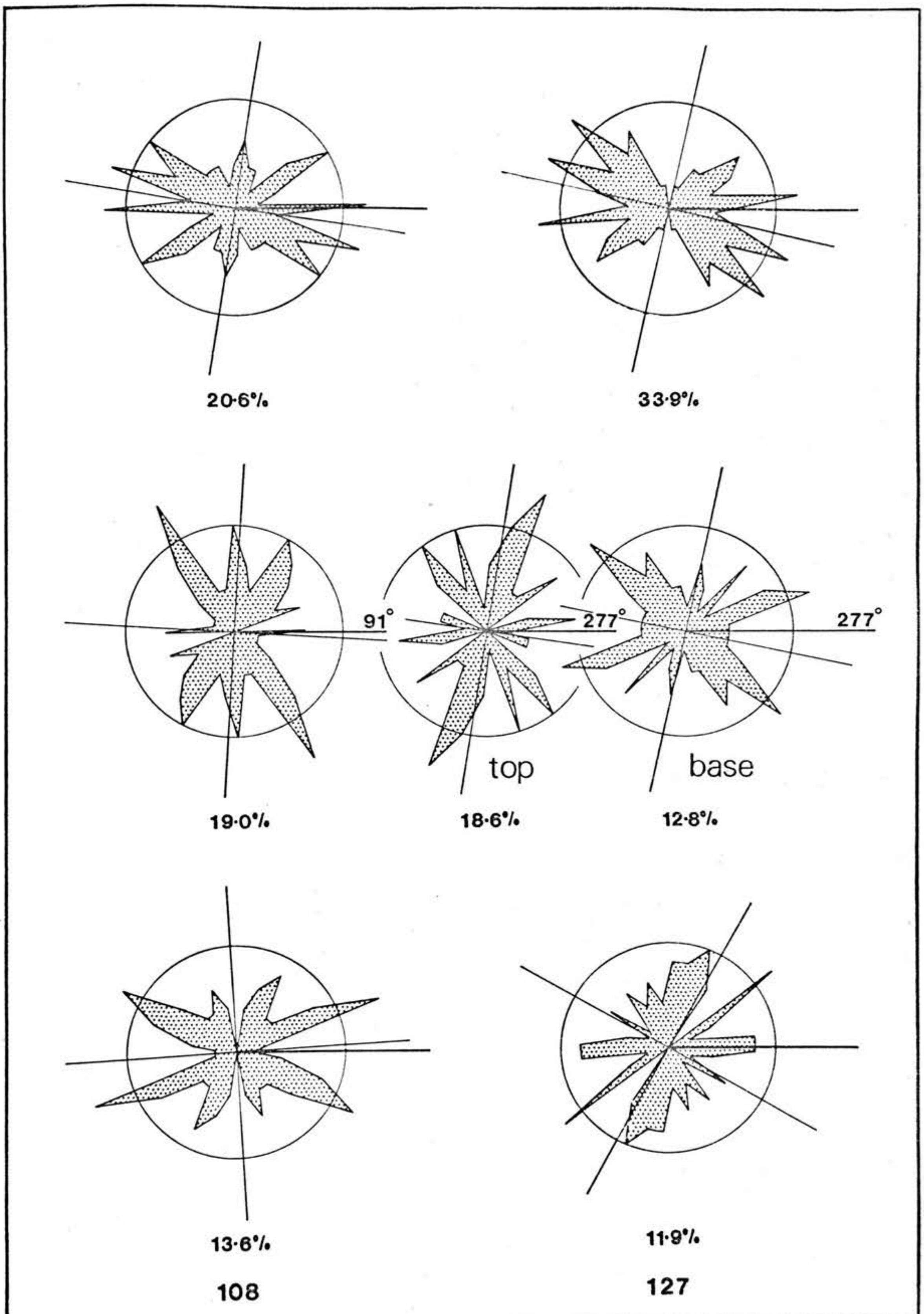


Figure 5.16

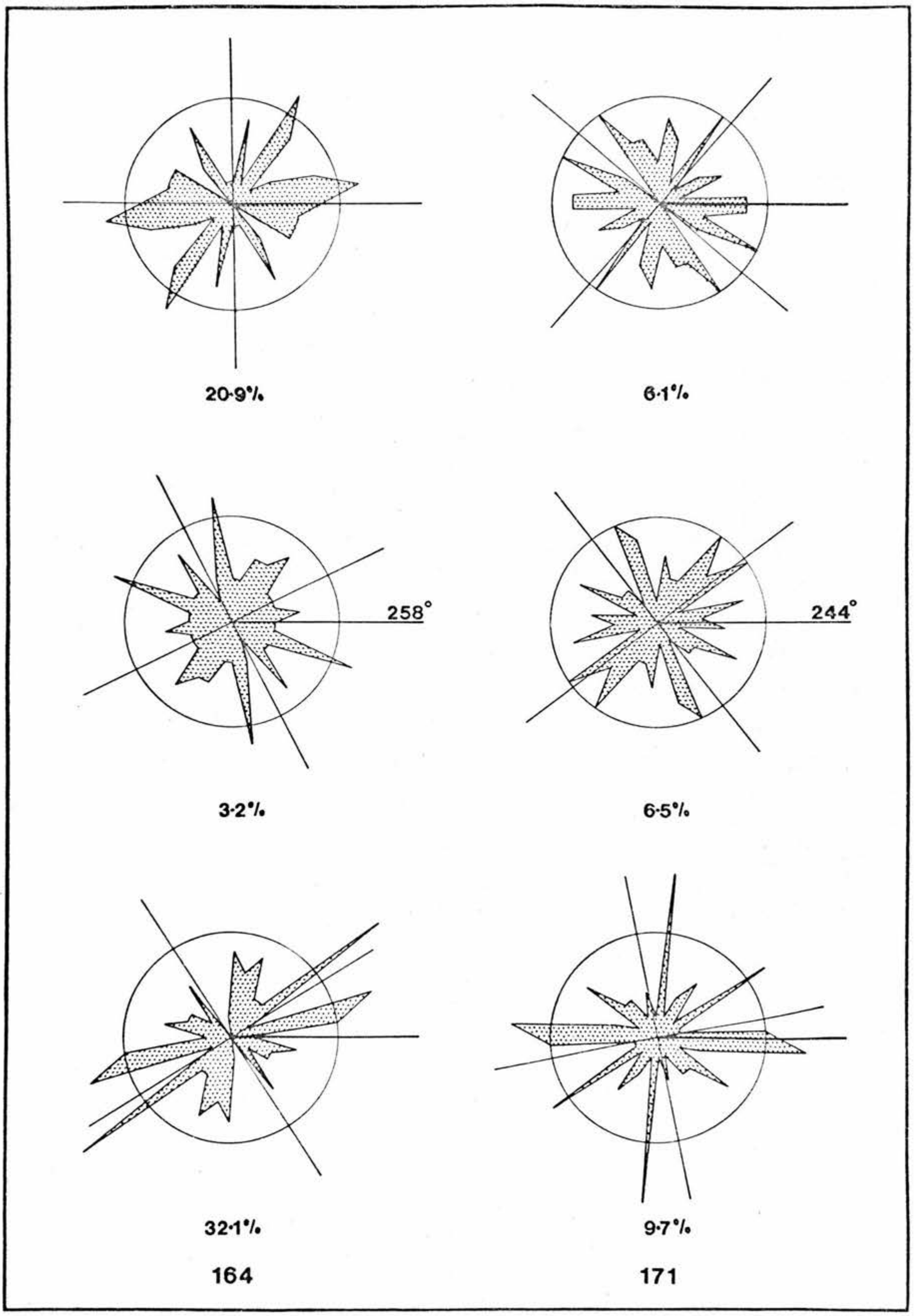


Figure 5.17

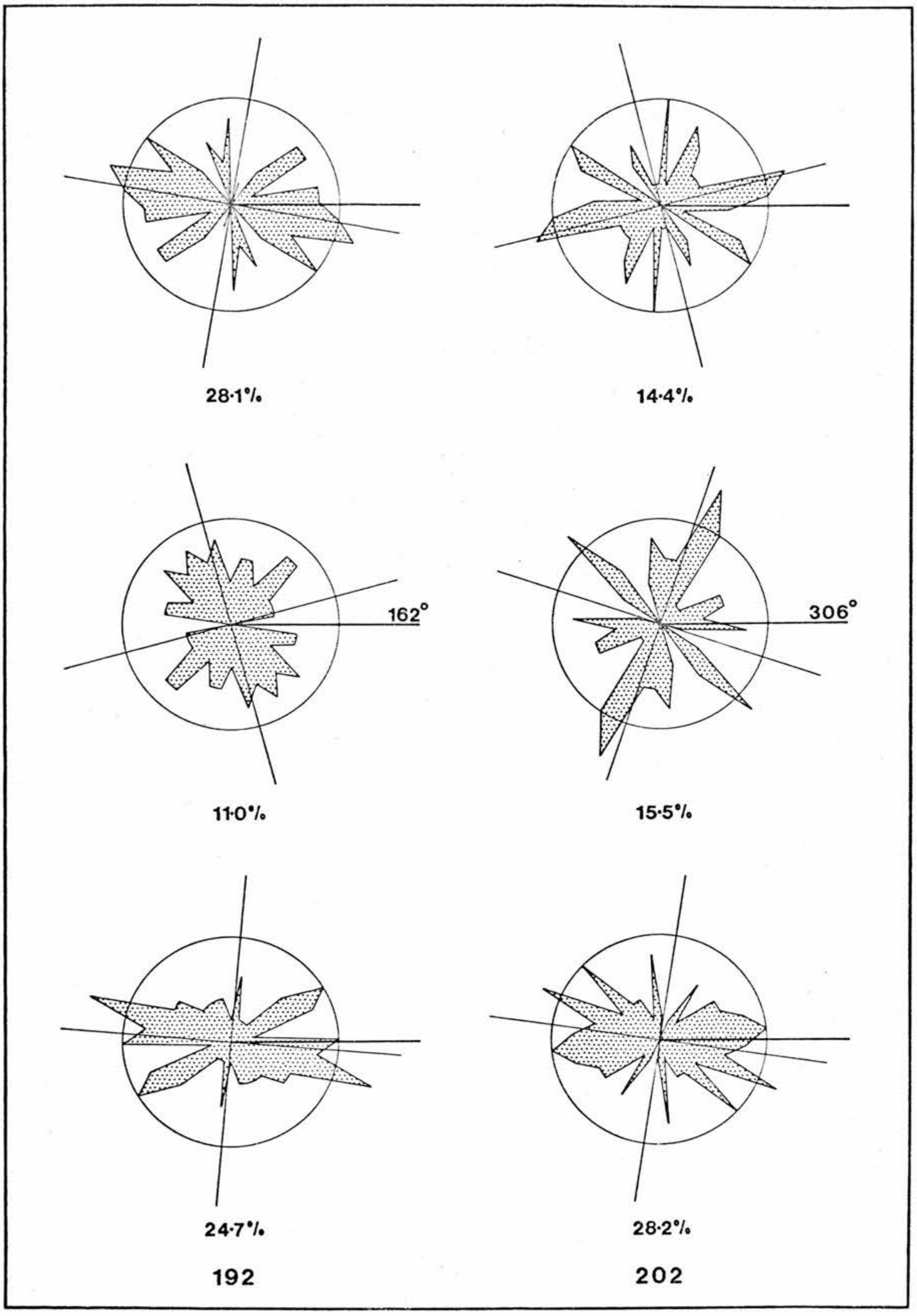


Figure 5.18

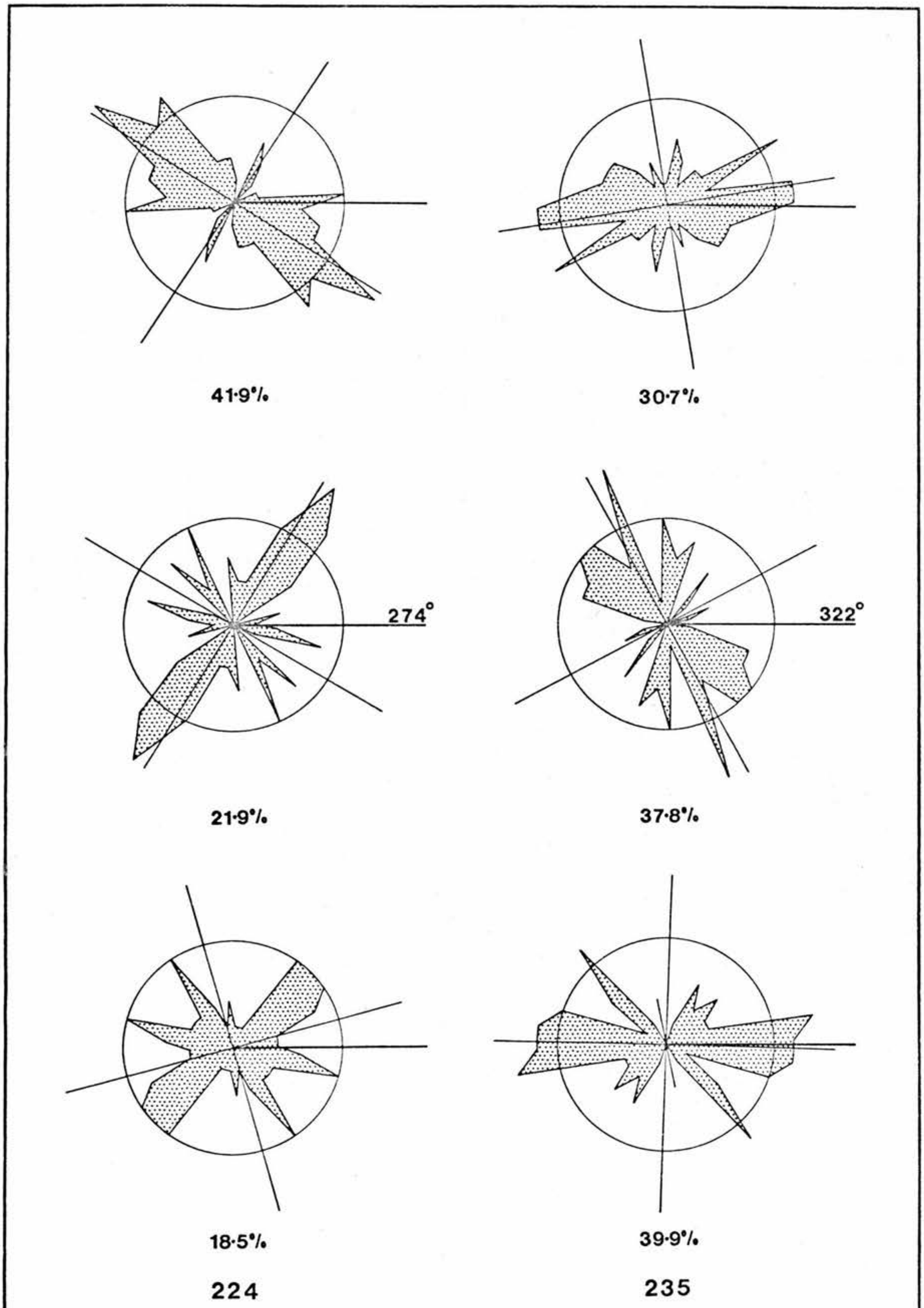


Figure 5.19

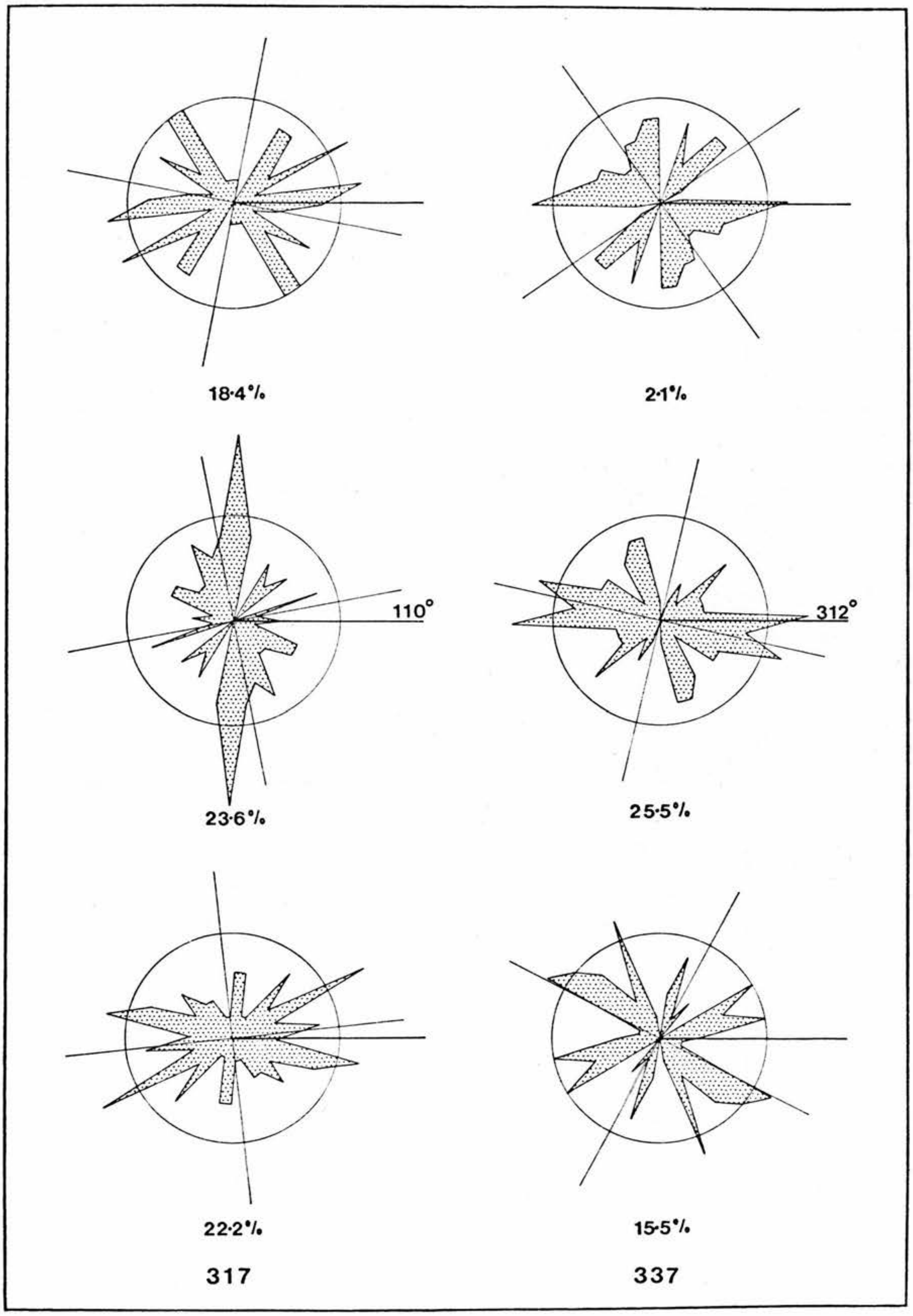


Figure 5.20

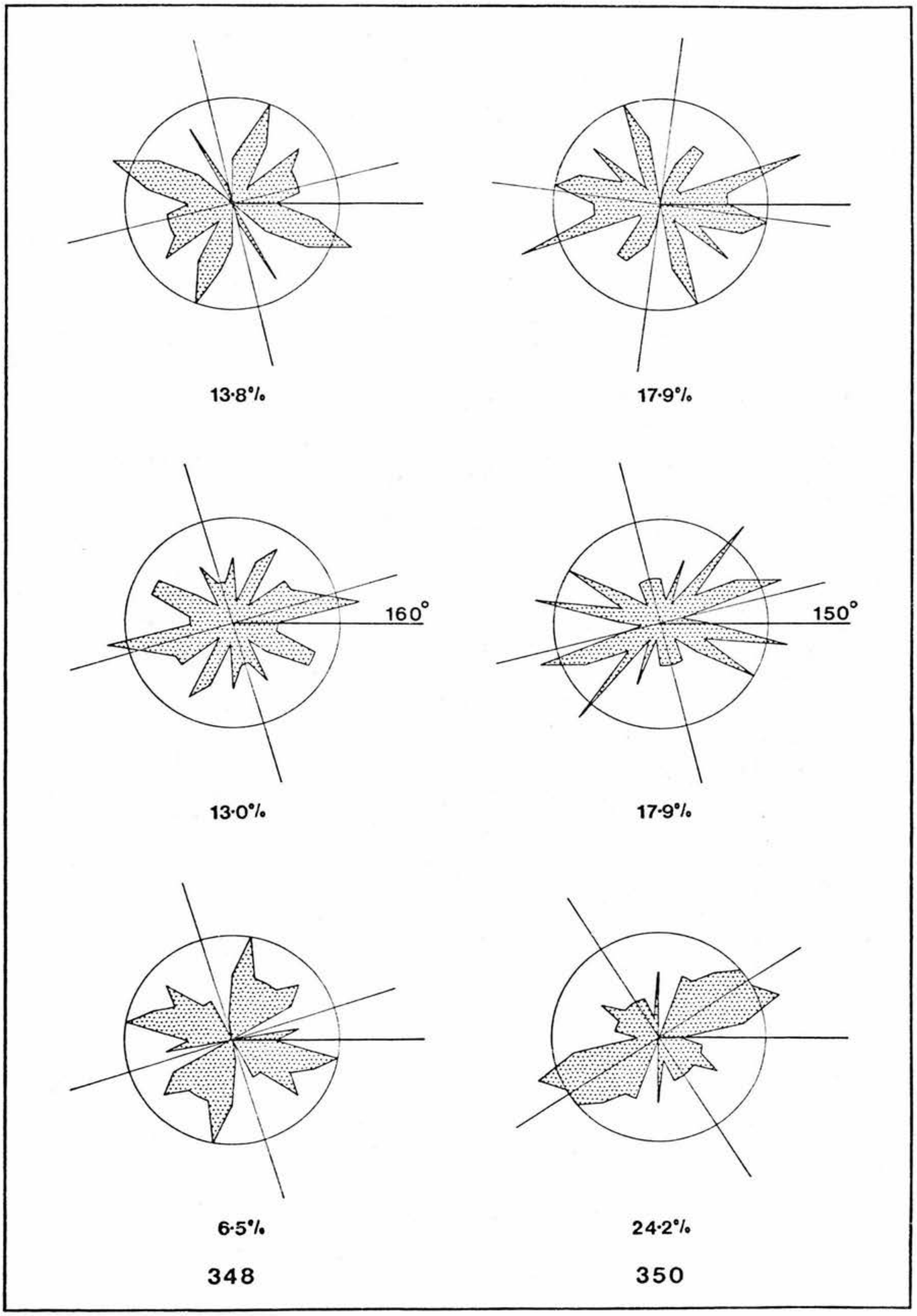


Figure 5.21

distribution. The results have the advantage of being independent of any a priori reference direction or origin. For a statistically significant orientation distribution at the 95% confidence level, for a sample of 50 stones, the strength (vector magnitude) must be greater than 24.5%. For a significant result at the 99% confidence level the strength must exceed 30.4%. Each diagram (Figures 5.14 to 5.21) is accompanied by the orientation strength values, and shows the calculated vector directions.

Granite Lobes:

Examination of the boulder orientation diagrams (Figures 5.14 to 5.19) reveals a general tendency for the boulders of the frontal parts of granite lobe risers to be oriented approximately at right-angles to the lobe axis, and for boulders in each of the two lobe sides to be oriented approximately parallel to the lobe axis. This tendency is not well marked in all of the diagrams. Only 15 of the 36 fabrics have statistically significant orientations (at the 95% level). Thus more than 50% of the samples do not have a well developed fabric.

Of the 3 statistically significant samples from the fronts of lobes (Lobes 83, 103, 235) the calculated vector direction lies at 70°, 84° and 61° respectively, to the lobe axis. Of the 6 statistically significant right-hand side samples (Lobes 29, 103, 127, 192, 224, 235) the vector direction lies at 0°, 5°, 13°, 9°, 33° and 10° respectively, to the lobe axis. The vector direction for the 6 statistically significant left-hand sides (Lobes 1, 83, 164, 192, 202, 235) are similarly oriented with respect to the lobe axis, at 5°, 33°, 22°, 4°, 8° and 1° respectively.

Significant vector directions in the 6 right-hand side samples tend to be directed towards the lobe axis (in the downslope direction) in 3 examples (127, 192, 224), to be parallel in one example (29) and to be directed away from the lobe axis in the other two examples (103, 235). Only one of the statistically significant left-hand side fabrics (164) tends towards the axis of the lobe, the other 5 being directed away from the centre.

Two fabrics samples were taken from the front of lobe 127

(Figure 5.16) from the finer material at the top of the riser and the coarser material at the base of the riser (see Boulder Size section). Neither section had a statistically significant orientation.

The possibility that all the fabric diagrams, including the non-significant ones, might conceal a more general tendency was investigated (Figure 5.22). All 12 fabric diagrams for the lobe fronts were combined by reducing them all to a common aspect (slope direction) and summing the values for each of the common 10° sectors, and similarly for the two groups of 12 fabrics for the two lobe sides. All three fabric diagrams have statistically significant (at the 95% level) calculated vector directions (more than 7.1%, for 600 samples). The preferred orientation direction for the composite lobe front diverges from the lobe axis by 86°. Each of the two sides have preferred orientation directions towards the lobe axis (in the downslope direction). The composite right-hand sample diverges from the long axis direction by 7°, and the composite left-hand sample diverges by only 2°.

Thus it is concluded that although the lobes do not currently have a fine-grained matrix that is susceptible to gelifluction, and despite the large size of the constituent boulders the fabric patterns suggest that the lobes originated by a mechanism analogous to viscous flow. In general the boulders exposed at the borders of these boulder lobes lie with their long axes tangential to the curved edges.

Three boulder fields, on the flanks of the two summits, were sampled to examine the fabric pattern of granite blocks that have not been rearranged into lobes. The fabric diagrams (Figure 5.24) show only one statistically significant prefered orientation direction (at the 95% level), that from the summit boulder field of Cuidhe Crom (18° slope). This fabric deviates from the direction of maximum slope by 39°; thus the blocks tend to be aligned obliquely to the gradient. A composite diagram constructed from the three boulder-field samples reveals a statistically significant orientation direction (more than 14.1% for 150 samples) at the 95% level. The composite diagram vector

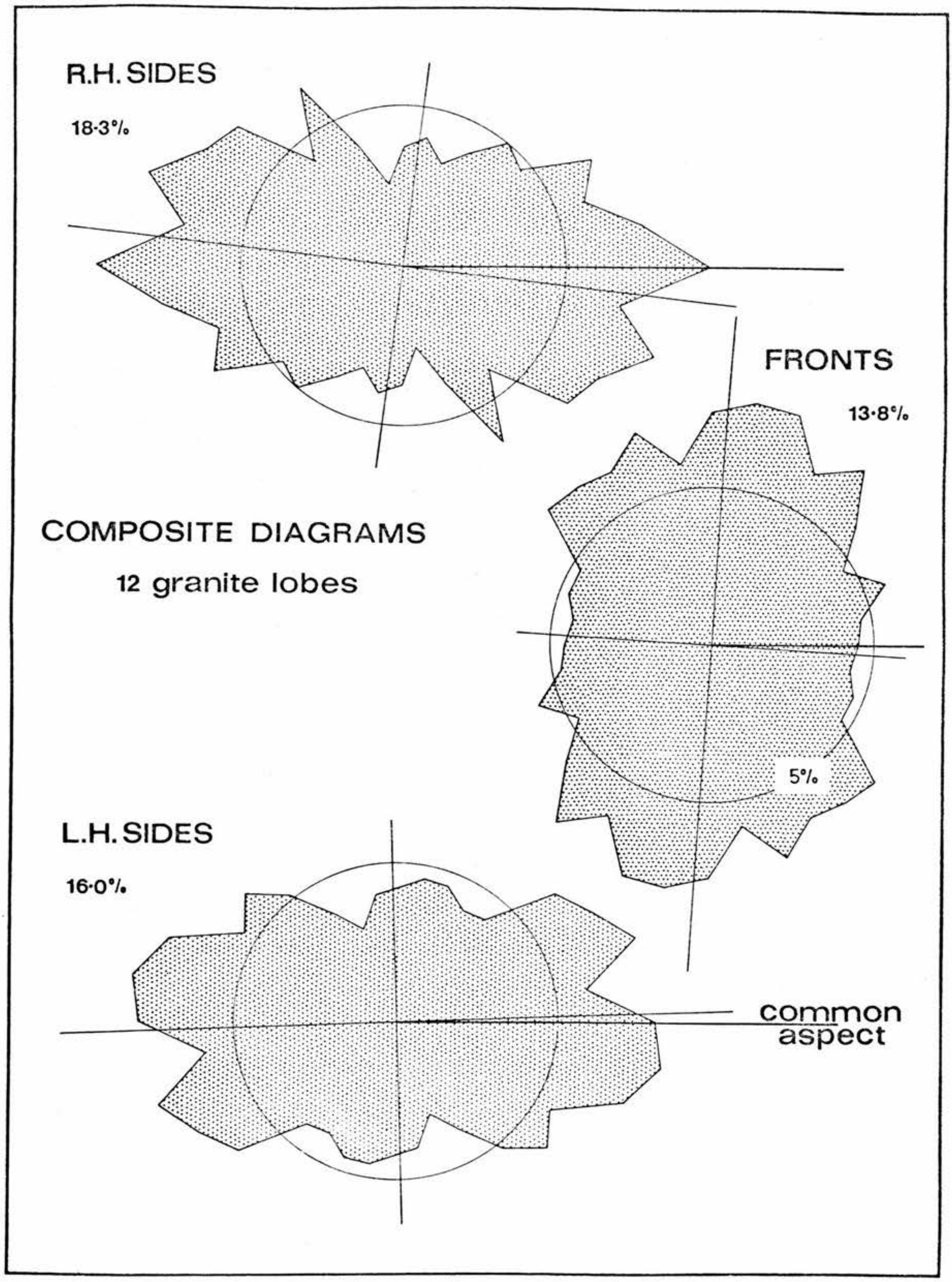

R.H. SIDES
18·3%
FRONTS
13·8%
COMPOSITE DIAGRAMS
12 granite lobes
5%
L.H. SIDES
16·0%
common aspect

Figure 5.22

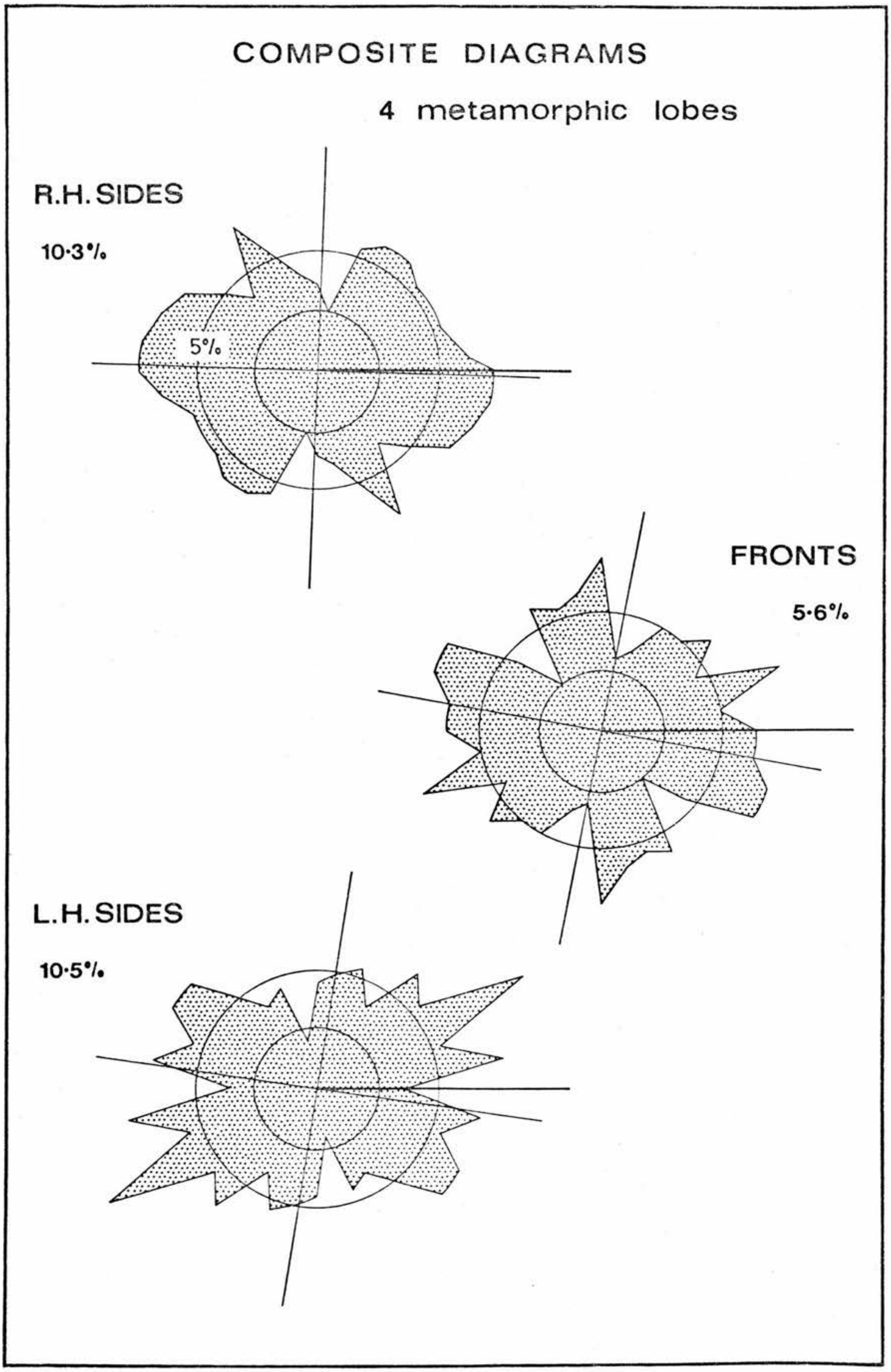

COMPOSITE DIAGRAMS
4 metamorphic lobes
R.H. SIDES
10·3%
5%
FRONTS
5·6%
L.H. SIDES
10·5%

Figure 5.23

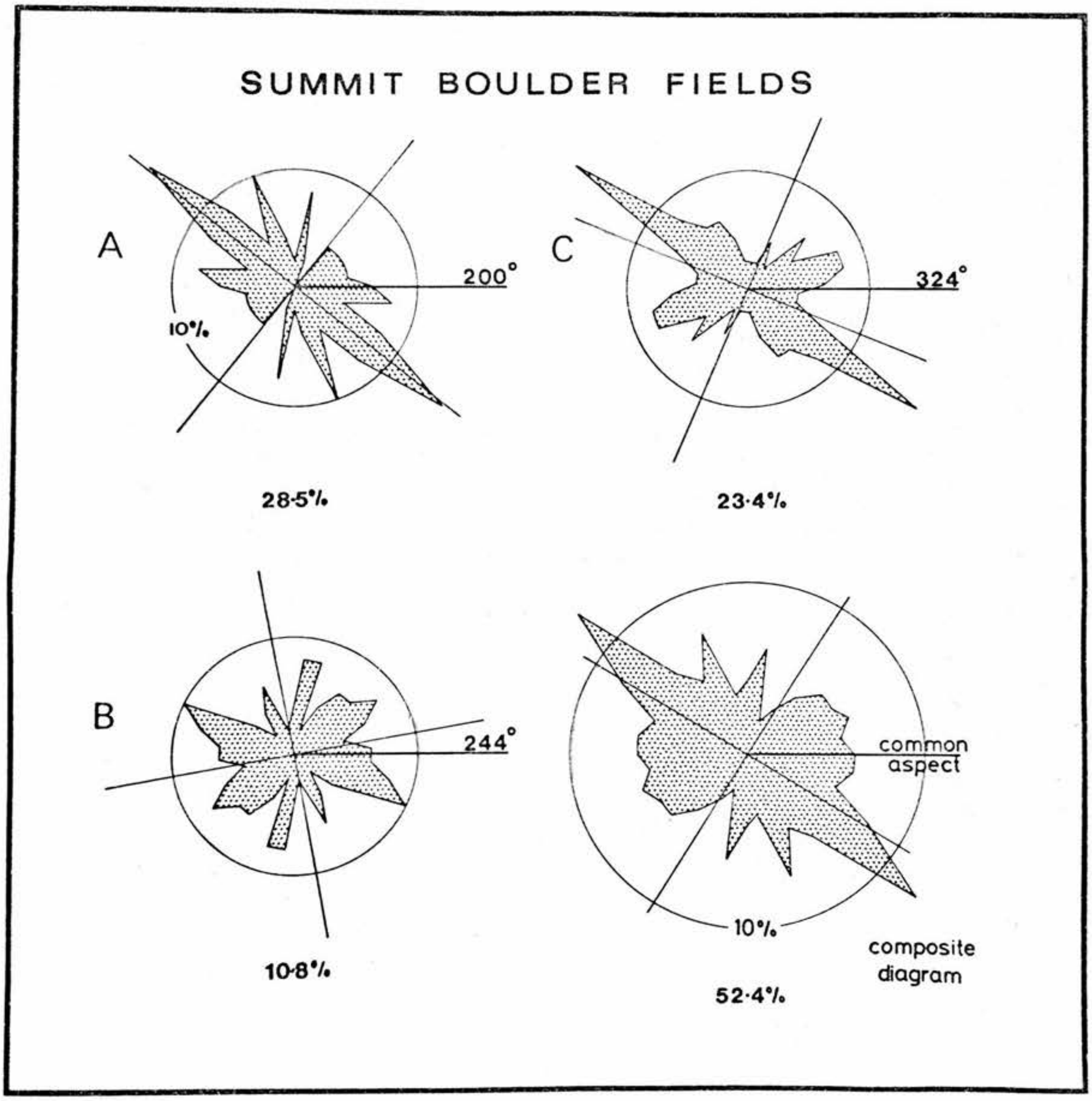

SUMMIT BOULDER FIELDS
A
200°
10%
28·5%
C
324°
23·4%
B
244°
10·8%
common aspect
10%
composite diagram
52·4%

Figure 5.24

deviates from the downslope direction by 31°. Caine (1972) determined from studies of blockfield fabrics in Tasmania that over large areas of the blockfields the vector direction was displaced away from the local slope direction by up to 20%. He was unable to explain this displacement, except to suggest that it may have been due to the effect of impeded movement during blockfield emplacement. Blockfield fabrics in the present study show a tendency to be aligned parallel to the local slope direction, rather than across the slope. The oblique orientation is possibly a response to subsurface bedrock forms, or to restricted flow in these situations.

The possibility of an increase in fabric strengths downslope was investigated by examining three samples from the summit ridge of Lochnagar. The summit boulder field of Cac Carn Mor (Figure 5.24) is situated upon the end of the summit ridge. Lobe 164 occurs about 190m downslope of lobe 171 in the summit col (Figure 5.17). No statistically significant preferred orientation is exhibited by the boulders of the summit boulder field sample, nor by the higher lobe (lobe 171). Only one sample from lobe 164 (the left-hand side) has a statistically significant preferred fabric. Similarly, lobe 224 occurs below lobe 235 on the slopes of Gathering Cairn. The uppermost lobe has a well developed fabric pattern on all three sides, all three samples being statistically significant. Lobe 224 has only one sample (the right-hand side) with a significant preferred orientation. No firm conclusions can be drawn from these two isolated investigations but the results suggest that, in general, the fabric strengths of boulder lobes do not increase with increasing distance downslope.

<u>Metamorphic Lobes:</u>

Similar sampling procedures upon four metamorphic lobes (317, 337, 348, 358) revealed rather more random fabric patterns than those determined in the granite lobes. The samples from each lobe all suggested a tendency towards a downslope orientation (Figures 5.20 and 5.21). Only one sample had a statistically significant preferred orientation direction, that from the front of lobe 337 (at the 95% level). This vector direction deviated by 17° from the downslope direction.

Composite orientation diagrams for the four lobes (Figure 5.23) suggest slight maxima in a downslope direction for all three sections of the lobe, but none is statistically significant (vector magnitude greater than 12.2% at the 95% level for 200 samples).

Metamorphic lobes appear to have less well developed fabrics than granite lobes. Whereas the boulders in the risers of granite lobes tend to be oriented tangentially to the lobe sides, the blocks in the metamorphic lobes generally tend to aligned in a downslope direction.

Part 2: Summary and Conclusions

Both granite and metamorphic lobes appear to be devoid of interstitial fine material between the boulders, at least in the upper parts of the tread and in the riser. The lobe treads are covered by a thick layer of peat supporting a dense moorland vegetation but the risers are usually free of vegetation. The lobes are boulder lobes rather than true stone-banked ones as there is no body of fine debris behind the riser wall.

Boulders ranged between an average size of 18.6cm to 137.1cm longest dimension in the granite lobes, and between 21.1cm to 42.0cm in the metamorphic area. Despite the large size of the boulders and the lack of fines the boulders showed a tendency towards a preferred fabric suggesting an origin by flow. Boulders in the side-risers of granite lobes tended to be oriented parallel to the lobe axis and boulders in the front riser tended to be oriented at right angles to the lobe axis. Boulders in all three situations in metamorphic lobes were aligned more or less parallel to the lobe axis. Boulders in summit boulder fields had a fabric direction roughly parallel to the slope direction but deviating by up to 39^{o} from it.

Boulder size does not appear to increase or decrease with increasing distance downslope, and the orientation strength of the boulder fabric does not increase downslope.

Part 3: Factors Affecting the Development of Lobes

The Influence of Terrain Factors upon the Characteristics of Lobes

It has been shown in the preceding sections that the several facets of lobes vary rather widely in their sizes and angular relationships; however, it should be noted that most of this variation occurs within narrow limits. Also, lobes have been located throughout a wide range of altitudes, slope angle and slope aspect situations. It seems reasonable to suppose that the terrain factors, singly or in combination, might exert a dominant influence upon the development of some or all of the characteristics of the lobes. Thus a change in the magnitude of one of the terrain parameters might explain changes in the observed size or form, or both, of the lobes.

This problem was approached initially by applying simple linear regression analysis techniques to test the possibility that a change in the magnitude of a terrain parameter might directly explain observed changes in lobe characteristics. Therefore if, for instance, the angle of the riser of lobes changed directly, or perhaps inversely, as the angle of slope increased then this relationship would be revealed by a high determination ratio (R^2 approaching unity). A low determination ratio (R^2 approaching zero) indicates a poor, or even non-existent, linear relationship.

Several of the lobe characteristics were correlated in turn with various terrain parameters and some of the lobe parameters. The results are presented below.

		Granite Area	Metamorphic Area
Riser Angle with	Aspect	0.003	0.160
	Slope Angle	0.298	0.294
	Angle Below	0.243	0.555
	Lobe Thickness	0.107	0.048
Riser Length with	Aspect	0.000	0.048
	Angle Below	0.108	0.157
Lobe Thickness with	Altitude	0.014	0.175

Aspect	0.001	0.031
Angle Below	0.011	0.242
Surface Angle with Slope Angle	0.567	0.177
Angle Below	0.500	0.307
Riser Angle	0.317	0.367
Lobe Width with Altitude	0.029	0.000
Aspect	0.003	0.001
Slope Angle	0.001	0.115
Angle Below	0.019	0.003
Lobe Length/Spacing with Altitude	0.023	0.022
Aspect	0.003	0.042
Slope Angle	0.021	0.009
Angle Below	0.000	0.131
Left-hand Length with Aspect	0.045	0.019
Slope Angle	0.003	0.001
Right-hand Length with Aspect	0.023	0.000
Slope Angle	0.003	0.001

It can be seen that no single factor explains more than 57% of the total observed variation of another. Thus, in the granite area, 57% of the total variation in the surface angle of the lobes is associated with changes in the slope angle, and only 18% in the metamorphic area. In the metamorphic area 56% of the total variation in the riser angle is associated with changes in the angle below, but only 24% in the granite area. These examples highlight the great variability that often appears between the value of the determination ratio for the same correlation in each of the two areas.

Among the three terrain parameters, the slope angle (and angle below) appears to explain more of the variations of other factors, than do either of the other two. Nevertheless, the slope angle appears to explain only a very small proportion of the observed variations of the measured lobe characteristics.

In an attempt to find fuller explanations of these variations the technique of multiple regression analysis was used. Multiple regression examines the relationship between a set of independent variables and a single dependent variable. The procedure is designed to produce a linear combination of independent variables that will correlate as highly as possible with the dependent variable. It has been shown above that the simple regression method of attempting to predict one variable by means of a related variable has yielded poor results. This may not be because the relationship is far removed from the linear one assumed, but is possibly because there is no single variable related closely enough to the dependent variable to yield good results. It is worthwhile to investigate the possibility that there are several variables that, when considered together, will serve as a satisfactory explanation of the observed distributions.

The following examples demonstrate the improved explanations achieved with multiple regression techniques.

		Granite sample	Metamorphic Sample
Riser Length with	Lobe Thickness	0.435	0.515
	Angle Below	0.593	0.518
	Surface Angle	0.774	0.601
Riser Angle with	Slope Angle	0.342	0.294
	Angle Below	0.352	0.603
	Lobe Thickness	0.470	0.627
Lobe Length/ Spacing with	Angle Below	0.002	0.131
	Lobe Thickness	0.044	0.170
	Altitude	0.066	0.174

Multiple regression indicates that the observed variations in lobe characteristics can be explained more fully when several factors are taken into account, rather than assuming that one other factor only might explain a large percentage of the variations. Thus it appears that in the granite area, 44% of the total variation in the length of the lobe risers can be explained by variations in the thickness of the lobe layer, but 59% can be explained by variations in the angle of the ground below the riser combined with changes in the thickness of the lobe layer. Finally, 77% of the total variation in the length of the riser can be explained by changes in the angle of the surface of the lobe combined with changes in the angle of the ground below the riser and changes in the thickness of the lobe layer. These three variables considered together explain 60% of the observed total variation of the riser lengths of metamorphic lobes. It can also be seen that 60% of the total variation of the riser angle of metamorphic lobes can be explained by variations in the slope angle combined with changes in the angle of the ground below the riser. The combination of these two variables explains only 35% of the total variation of the riser angle of granite lobes.

Summary and Conclusions

It has been shown that within the two areas, different variables appear to exert different degrees of control over others, but no single variable is able to explain more than 57% of the observed variation of another in any area. No combination of variables has been shown to be able to explain more than 77% of the total variation.of another. These findings suggest that despite the variety of parameters measured much necessary information is lacking. The detailed development of lobes will also depend upon the size and shape of the material incorporated in each lobe, hence the way in which it is able to move in response to frost processes and gravity. The form of the bedrock or sub-lobe surface will determine the resistance to movement at the base of the lobe- layer, as also will the presence of a layer of fines at the base or at depth within the lobes. The size and the pore spaces, dependent upon the size of the material and its packing, will influence the frost-susceptibility of the material.

Thus it is concluded that information about the mechanical and flow characteristics of the lobe material and the sub-lobe surface is a necessary supplement to the terrain characteristics considered here before the size distribution of lobes can be more fully understood.

Age of the Lobes: The Distribution of Granite Lobes in Relation to the Presumed Limits of the Loch Lomond Corrie Glaciers

It has been pointed out that lobes occur upon the upper sections of many slopes above the Mount Keen and four Lochnagar corries, and above the Loch Muick trough, but cease abruptly at the lateral limits of the presumed Loch Lomond age corrie glacier limits (Altitude section). This phenomenon exists despite the fact that the slopes below these abrupt lower terminations appear to be otherwise suitable, and that lobes occur to below these levels on the slopes of the hills near the corries. Such a relationship suggests that lobes may have existed below their present levels in these situations, possibly descending to near the floors of the corries, but were removed by the ice of the Loch Lomond Stadial. Alternatively the lobes could have formed while ice occupied the corries, and developed down to the ice margin.

Careful searching of the slopes within the presumed corrie glacier limits did not reveal any sign of the huge boulder lobes that were present on the slopes outside these limits. Some of the abundant bouldery debris on slopes within the corries appears to have been affected by some down-slope transfer, such as on the slopes below the Meikle Pap Col (NO 257858), and at the back of Coire na Cive (NO 248865). In these two situations the debris has an irregular, intermittent low-stepped appearance but no individual terrace or lobe forms have been produced, similar to those occurring immediately outside the Lochnagar corrie lateral moraine on the flanks of Meikle Pap (NO 258861). Well developed lobes are absent from these slopes of which the slope angles, debris size, aspects and altitudes are all within the range of limits that have been shown to be favourable to lobe development on other slopes outside the mapped glacier limits. This evidence strongly suggests that the large granite boulder lobes examined throughout the Mount Keen and Lochnagar Massifs have not formed, or moved substantially, since the decay of the Loch Lomond age corrie glaciers. Such a conclusion is based firstly upon the distribution of these features outside and immediately adjacent to the limits of the presumed Loch Lomond age corrie glaciers, and secondly upon the preceding study of the nature of these lobe features.

Tufnell, (1969) has described active congelifluction lobes in Northern England whose risers are only up to 60cm high. Ball and Goodier working in North Wales recognised contemporary stone-banked lobes with fronts up to 0.5m high, and a lobe formed of the collapsed debris of a (pre-nineteenth century) dry-stone wall containing debris up to 30 to 50cm diameter (Goodier and Ball, 1969). King, (1968, 1972, p.165) and Kelletat (1970a) supported Galloway's (1958) hypothesis that turf-banked lobes, with risers about 30cm high, are active in Scotland at the present day. White and Mottershead (1972) have shown that a turf-banked terrace on Ben Arkle, Sutherland, has moved downslope since about 5,200 B.P., possibly at about 500 B.C. or in the Little Ice Age (A.D.1550-1850). Eggeling (1964) reported that a small (0.4m high) stone-banked terrace on the Island of Rhum moved during the winter of 1963. These features all either contained a high proportion of fines, or, as in the case of the North Wales examples, were situated upon a soil layer containing fine material. Thus all these currently active examples were associated with fine grained debris that would be readily affected by frost-creep and gelifluction. Also, they were all small features, with risers less than 1m high. The granite lobes in the present study had no interstitial fine material, and 72% had risers of more than a metre high. They also had, in most cases, boulders of a larger diameter than those contained in the currently active features, and were not developed upon a soil or fine debris layer, but upon the bouldery debris mantle of a lower lobe layer.

Workers studying the development of contemporary gelifluction lobes in Scandinavia and the arctic have emphasised the importance of thoroughly water-saturated fines to promote movement. The water usually comes from melting snow, so contemporary lobes most frequently occur upon leeward snow accumulation slopes, especially below late-lying snow patches (eg. Williams, 1957a, p.44; Rudberg, 1962, 1972, p.224; Washburn, 1967, p.73; Raup, 1969, p.137; Benedict, 1970). It has been shown that lobes in the granite area appear to prefer west-facing snow accumulation slopes (Aspect section). The apparent absence of fines in the matrix of the lobes indicates that these lobes cannot move by saturated flow and true gelifluction. Some authors have suggested that various periglacial boulder concentrations, such as block-lobes and boulder fields, may be inactive today due to washing out of the fines (eg. Jahn, 1967, p.p.214-215; Caine, 1968; Smith, 1968; Perov, 1969; Washburn, 1973, p.427; Embleton and King, 1975, p.118). Galloway (1961b) suggested that this mechanism had caused the stabilisation of lobes on Ben Wyvis, and on Lochnagar (1958, p.134). Such a mechanism seems unlikely, due to the thick peat cover over the slopes and lobe treads, effectively insulating the debris mantle from direct rainwash effects, and also promoting weathering of the boulders as was seen at the base of the pits in the treads of the excavated lobes. This peat layer would serve to produce fines, as well as promoting only slow percolation of water into the lobe.

A more likely possibility is that this debris never had abundant fine materials on these slopes. It is envisaged that the lobes moved by a process analogous to rock glacier creep in which the interstices of the lobes were filled with ice. Many active rock glaciers have been described that are masses of coarse debris and interstitial ice, owing their motion to the flow of the ice (eg. Wahrhaftig and Cox, 1959; Foster and Holmes, 1965; White, 1971). According to Wahrhaftig and Cox (1959, p.433) the conditions necessary for the growth of rock glaciers are an abundant supply of coarse blocky debris and a climate conducive to the accumulation of ice in its interstices. The talus must have large interconnected interstices in which ice accumulates from drifting snow or the freezing of water. On west-facing slopes the lobes in the present study area are facing the direction of the main snow-bearing winds; thus they are likely to have snow blown in between the boulders. They would also be kept relatively free of surface snow and so be exposed to temperature fluctuations causing creep, whereas the features on the lee accumulation slopes would be insulated by a mantle of drifted snow. The slopes in the area are covered with coarse blocky debris of a similar size to that reported as occurring in active rock glaciers, with a mean size of between 0.5m to 1.0m (Domaradzki, 1951, Roots, 1954, p.p.27-28; White, 1971, p.49) Thus, except for the configuration of the debris, the conditions are similar to those in rock glaciers.

It is envisaged that such a mechanism could only have operated during the climatic deterioration associated with the Loch Lomond Stadial. It is now being increasingly accepted that the last great ice sheet build up in Scotland began about 25,000 years ago and reached its greatest extent by 17-18,000 years ago. Such an ice cover would probably have removed all traces of any periglacial features that might have formed during the climatic deterioration associated with this glaciation. Periglacial features may have begun to form during the deglaciation, which was completed by about12,500 years ago. According to Coope and Brophy (1972) by about 13,000 years ago summer temperature conditions in North Wales were at least as warm as those of today. It is unlikely that any ice would have remained in the South East Grampians, or indeed, in Scotland as a whole (Sissons, 1974b, p.315; 1976, p.90), much after this time. Thus, the lobes must have begun to form after this period, unless some began to develop upon ice-free upland areas during cold fluctuations of the deglaciation.

A deterioration of the climate began about 12,000 radiocarbon years ago (Coope et al.,1971), and by 10,800 B.P. the July mean temperatures were about 4° or $5^{\circ}C$ lower than at the present day. This suggests that the lobes may well have begun to form after about 12,000 radiocarbon years ago. The ice that built up in the corries probably reached its maximum extent by about 10,300 B.P., leaving the well defined end moraines (described in Chapter 3: Map 5.1). It was during this period that climatic conditions would have been suitable to allow interstitial ice to form in the granite debris and cause the material to flow. That major movement has not occurred since this period is demonstrated by the absence of lobes within the glacier limits, and the well marked lateral boulder moraines across steeply sloping ground that have not been disturbed by periglacial activity.

Some settling, or slight reactivation of the lobes during the cold periods of 600-500 B.C. and the 'Little Ice Age' (A.D. 1550-

1850 c f. White and Mottershead, 1972), may have occurred since the lobes were formed and moved into their present position, but this can only have been minimal.

Age of the Lobes: Summary and Conclusions

Thorough investigations have demonstrated that the large granite boulder lobes that are well developed upon the slopes of the Mount Keen and Lochnagar Massifs are not present anywhere inside any of the four corries presumed to have been occupied by ice of the Loch Lomond Readvance. Lobes on the slopes above the corries terminate at, or above the mapped lateral limits of the corrie glaciers, and no periglacial rearrangement of the lateral boulder moraines has been observed. From this evidence it is concluded that the boulder lobes were developed during the climatic deterioration associated with the Loch Lomond readvance, probably between about 12,000 and 10,300 years ago. They do not appear to have moved since that time, even during the cold periods of the post-glacial.

These conclusions lend support to the view (Sissons and Grant, 1972; Sissons, 1972, 1974c, 1975) that large granite boulder lobes similar in size to the ones examined here might be used as supplementary evidence when identifying the ground occupied by glaciers of the Loch Lomond readvance. Small lobes formed in fine material or upon a layer of finer material have been shown to be active today in many areas. Similar small lobes have been identified in several parts of north-west Scotland upon ground presumed to have been covered by Loch Lomond ice, such as in the corrie above Loch Dionard (NG 341498: J.B.Sissons, personal communication) and in Coir' an Leth-uilt (NG 987548) and Maol Chean-dearg (NG 937492: M.Jackes, personal communication).

CHAPTER 6.

Boulder Terraces

Introduction

Gelifluction sheets, or the frost-moved slope regolith of periglacial regions, may have downslope edges that show a bench-like or lobate form. The latter features are a result of the existence within the mantle of zones of relatively rapid flow alternating with zones of slow or zero flow and were examined in the previous chapter. Benches have a pronounced terrace-form, with their longest dimension parallel to the slope contour or deviating by up to 45^{o} from that direction (Washburn, 1973, p.189). The difference between lobes and terraces is purely morphological, but it reflects the pattern of movement within the regolith.

Terraces were infrequently developed upon the hill slopes of the granite areas. Only 29 examples were located upon the hill slopes from which 300 granite lobes were sampled. Similarly in the metamorphic area terraces were rare upon the slopes sampled during the lobe survey. Previous examinations of periglacial mass-wasting landforms in the British Isles predominantly described small-scale turf-banked or stone-banked terraces (see Chapter 5 - Previous work). The scarcity of terrace-forms in the present study area seems anomalous in view of the fact that these features appear to be widely developed elsewhere. It has been pointed out (Chapter 5) that many authors have failed to distinguish between terraced and lobate forms and referred to all such landforms as terraces, benches, steps or garlands. Thus it is possible that terraces may be less widespread than the literature suggests, and consequently lobes more common.

Terraces in the Granite Areas

A total of 29 boulder terraces were identified in the granite study areas of the Lochnagar and Mount Keen Massifs. They ranged in altitude between 650m (Coire na Ciche: NO 272867) and 890m (Meikle Pap: NO 262860). Twenty five boulder terraces occurred on the west-to north-facing slopes (279^{o} to 8^{o}) of Meall an Tionail between 740 and 770m. These terraces were developed to the exclusion of lobes, beginning where the lobes faded out as the slopes approached a north-facing aspect. Other terrace examples occurred singly, among the lobes. The Coire na Ciche example (650m) was situated upon a north-west-facing slope (290^{o}), and the Meikle Pap example upon an east-facing slope (98^{o}). Two terraces upon the flanks of Gathering Cairn were situated at 750 and 730m upon 298^{o} and 248^{o} facing slopes.respectively.

Terraces were found on slopes with gradients between 14^{o} and 22^{o} (mean 19.6^{o}). The angle of the surface below the risers of granite terraces ranged from 3^{o} to 25^{o} (mean 13.8^{o}). The surface below the riser was usually less steep than the overall slope. Thus in only 2 cases was the angle below steeper than the slope angle (by 4^{o} and 5^{o}). The angle below was less steep by from 1^{o} to 17^{o} (mean 6.6^{o}).

The riser angle of the terraces ranged between 23^{o} and 34^{o} (mean 28.8^{o}), and was always steeper than the angle below (range 3^{o} to 28^{o}: mean 15.0^{o}). Terrace surfaces had slopes in two directions, a downslope gradient and an across slope gradient. The downslope gradient ranged from 6^{o} to 26^{o} (mean 12.4^{o}). In 3 examples the terrace surface sloped at the same angle as the ground below the riser, was steeper in 11 examples (range 1^{o} to 4^{o}: mean 2.5^{o}) and was less steep in 15 examples (range 1^{o} to 11^{o}: mean 4.5^{o}). Across slope gradients ranged from 2^{o} to 12^{o} (mean 4.6^{o})

Risers varied in length from 2.9 to 16.7m (mean 7.8m) and terraces were from 0.3 to 4.9m thick (mean 2.0m). The length of the terraces, parallel to the contours, ranged from 12.5 to 99.0m (mean 29.4m). They were usually almost straight in plan, only examples nos. 1, 28 and 29 being irregularly lobate. Terraces were spaced at between 5.0 and 98.0m (mean 18.4m) apart down the slope.

Risers of the granite terraces tended to be almost straight and approximately parallel to the slope contour. They deviated from this direction by between 1^{o} and 18^{o} (calculated normal to the slope aspect direction, with the exception of terrace no. 24 (deviation 31^{o}). The overall mean deviation was 8.8^{o}. The terraces were oblique in a left-hand or right-hand sense, that is descending to the observer's right or left when looking upslope. Twenty terraces were oblique in a left-hand sense, and 9 in a right-hand sense. No consistency in the direction of deviation was apparent. Thus terraces nos. 12, 14, 18, 20 and 21 succeeded each other in ascending order on the north-west-facing slopes of Meall an Tionail (750 to 770m). They were oblique in left-hand (13^{o}), left-hand (6^{o}), right-hand (14^{o}), right-hand (5^{o}) and left-hand (10^{o}) senses respectively.

An analysis of the size of boulders making up terraces nos. 1, 7 and 16 revealed that the boulders were a similar size to those making up the lobes. The average lengths of the a-axis of 50 boulders in the riser of each terrace were 87.3cm, 69.5cm and 73.4cm respectively. The fabric of the risers of terraces nos. 1, 7, 16 and 23 were analysed by taking two samples of 50 stones each from the right-hand and left-hand halves of the risers. Four of the eight fabric samples (Figures 6.1 and 6.2) have statistically significant preferred orientation strength values (more than 24.5% at the 95% confidence level). The preferred orientation direction tended to be at right angles to the direction of maximum slope and deviated by between 64^{o} and 86^{o} from it. There was no consistency apparent in the direction of the deviations, both being oblique in a left-hand sense in terrace 7, or converging downslope towards the centre of the terrace in terrace 16. Composite fabric diagrams produced from the data for the four right-hand and four left-hand sides (Figure 6.3) both show significant orientations (12.2% at the 95% confidence level for 200 samples) Both deviate by 79^{o} from the downslope direction, both in a left-hand sense. Three of the terrace fronts (7, 16 and 23) were oblique to the contours in a left-hand sense so the composite fabrics may result from this fact.

A pit dug into the tread of terrace no. 16 revealed 0.7m of peat upon large boulders with no interstitial fine material. This finding is in accord with the excavations of lobes (Chapter 5) and suggests that the development of terraces was not due to the localised presence of interstitial fine material. The risers of all the terraces were composed of boulders with no evidence of fine material and all were unvegetated. Terrace treads were vegetated with a moorland vegetation consisting predominantly of vaccinium and rhacomitrium.

Terraces in the Metamorphic Area

Terraces were extremely rare in the parts of the metamorphic

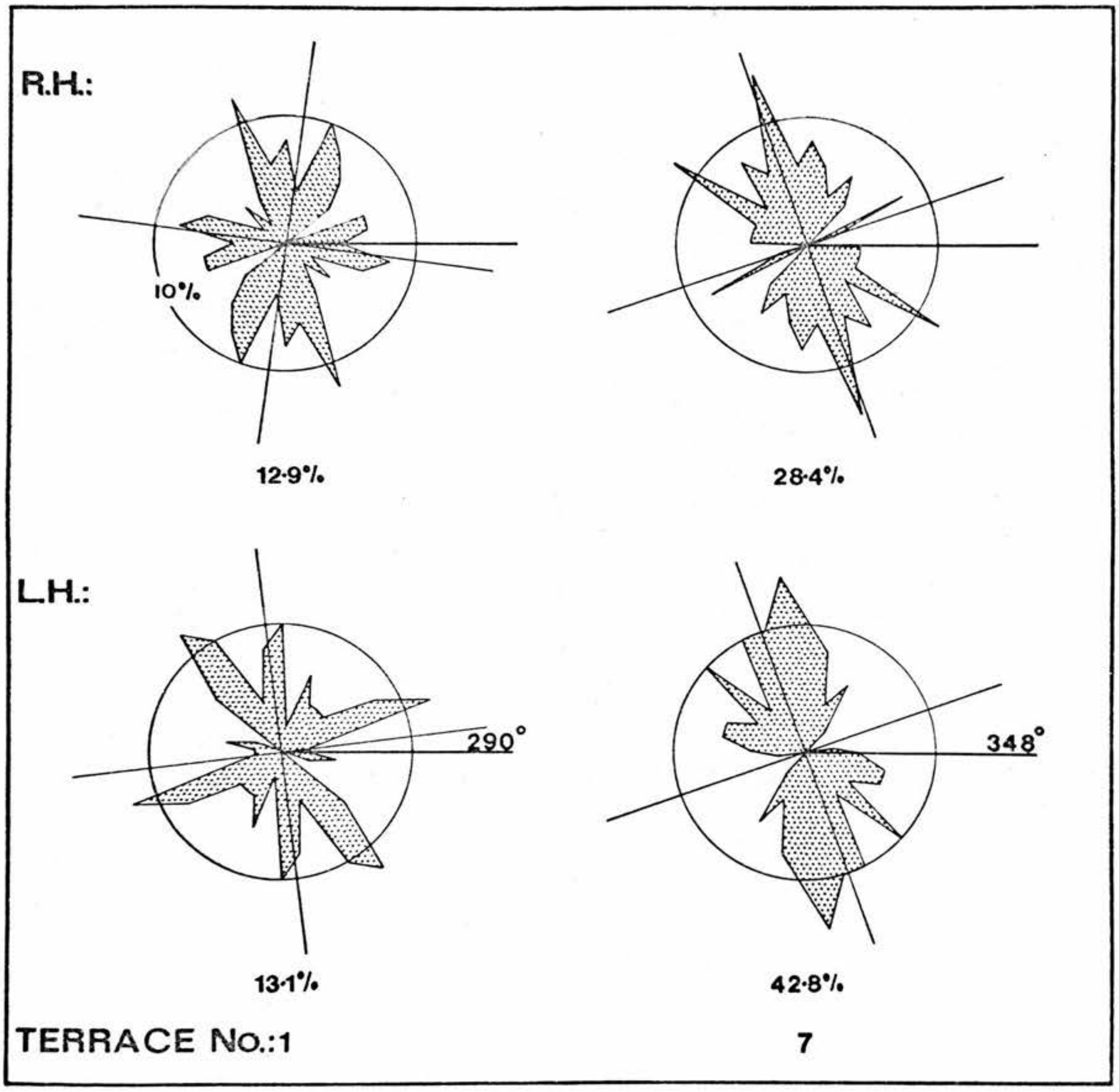


Figure 6.1

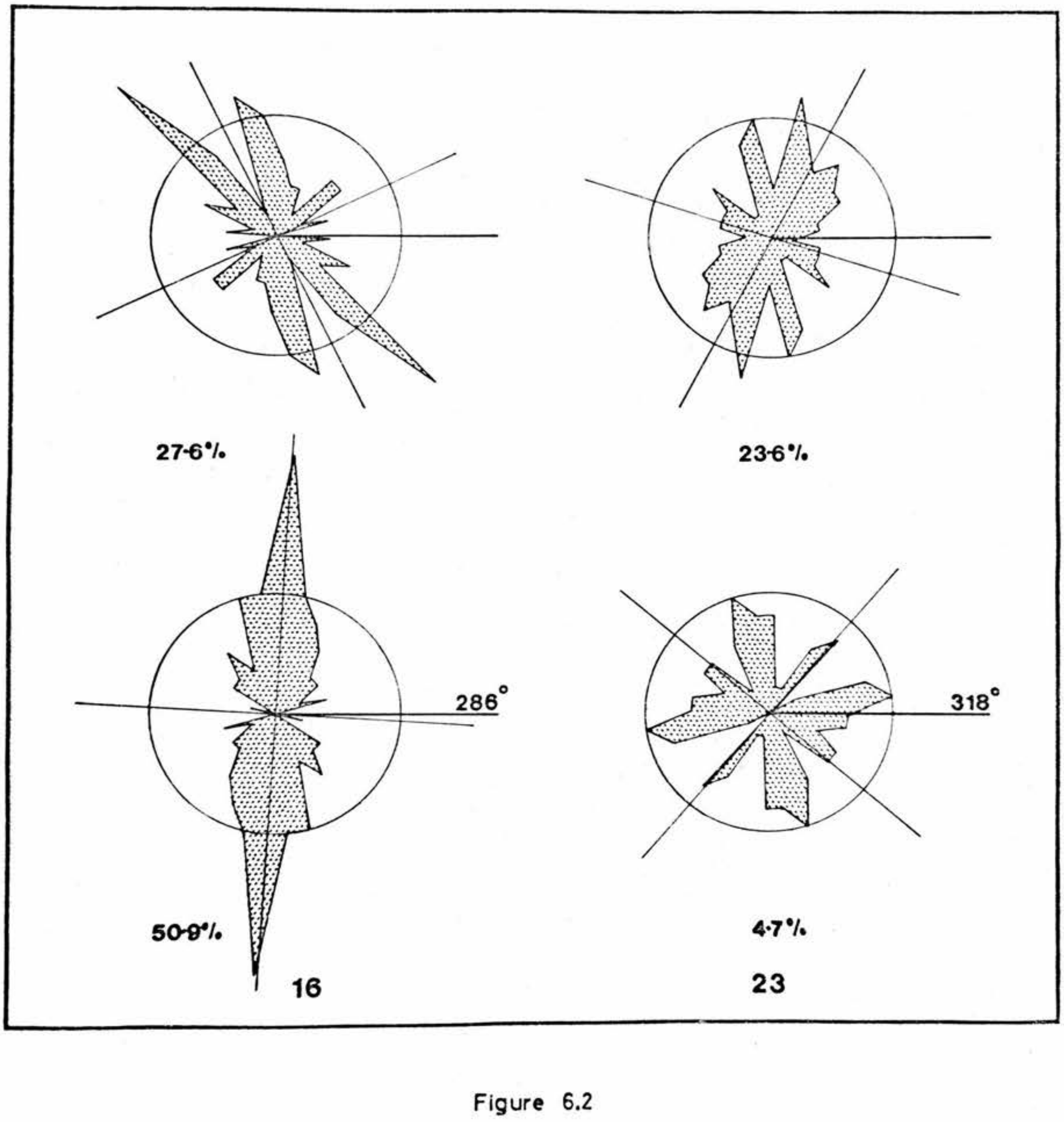


Figure 6.2

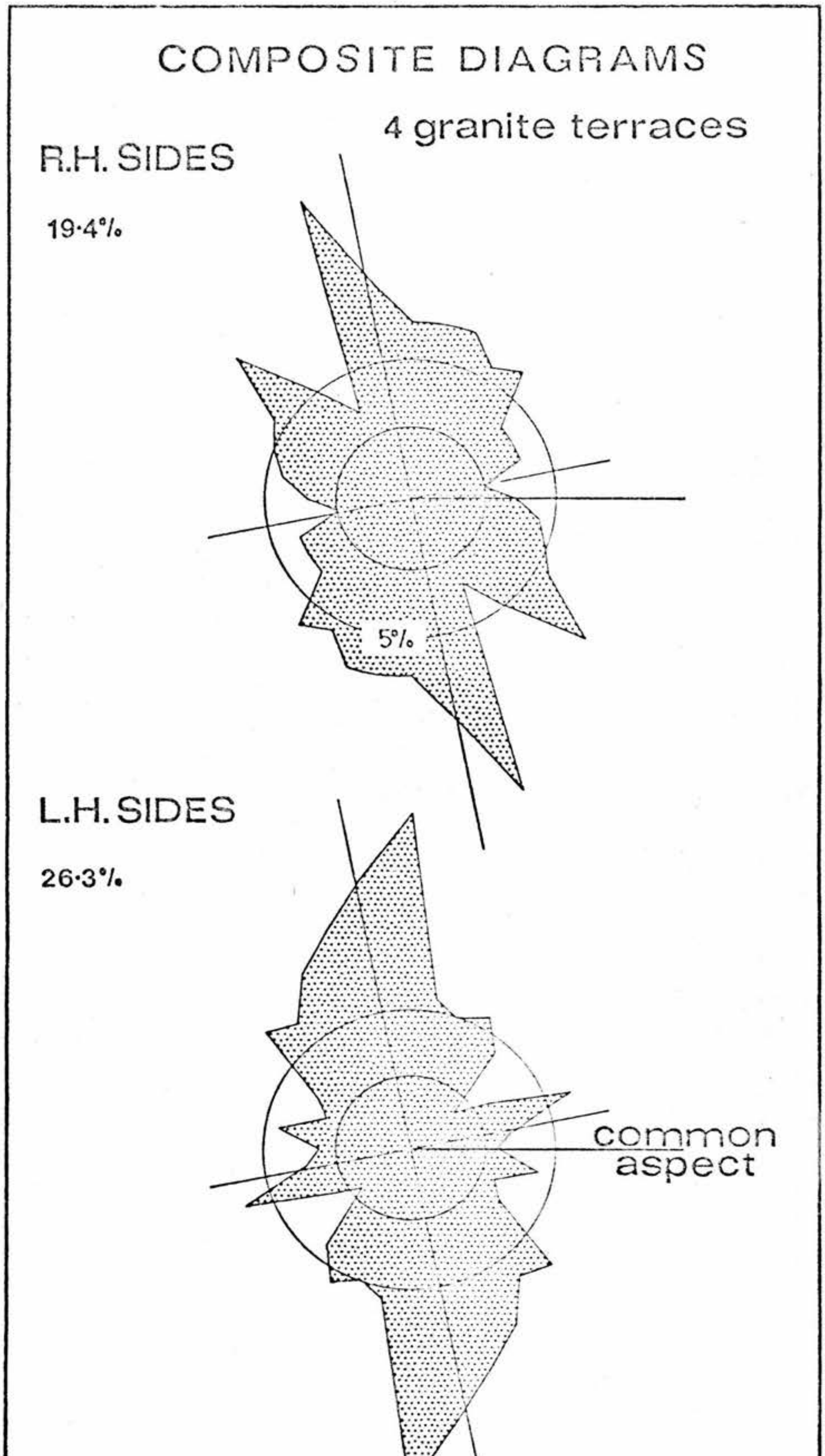

COMPOSITE DIAGRAMS
4 granite terraces
R.H. SIDES
19·4%
5%
L.H. SIDES
26·3%
common
aspect

Figure 6.3

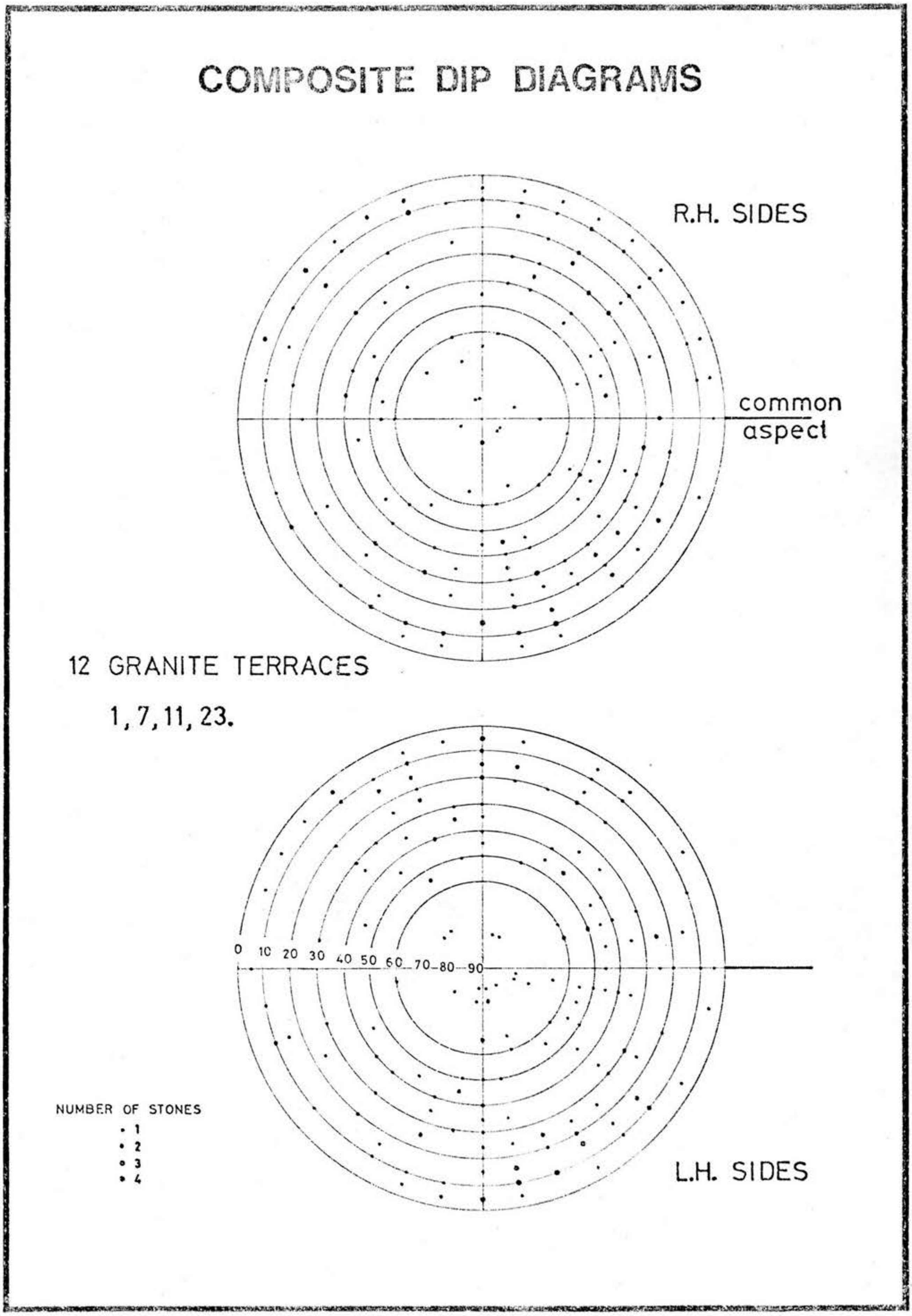

COMPOSITE DIP DIAGRAMS
R.H. SIDES
common
aspect
12 GRANITE TERRACES
1, 7, 11, 23.
0 10 20 30 40 50 60 70 80 90
NUMBER OF STONES
1
2
3
4
L.H. SIDES

Figure 6.4

area that were investigated. Those that did occur were considerably smaller than the granite terraces. Risers were less than 0.5m high, and the treads were only up to 2.5m wide but ran along the contour for up to 40m. The east-facing slopes of Carn Chrionaidh had the most extensive development of terraces, on slopes ranging from 18° to 25°. They were developed on small blocky quartzite debris (average length of blocks 15.4cm and 18.7cm in two examples) with risers free of vegetation and treads supporting only patches of vaccinium. The risers sloped at about 30°–36°.

Summary and Conclusions

Terraces occurred infrequently in the granite and metamorphic study areas. Granite terraces were of a similar order of size to the granite lobes, but metamorphic terraces were considerably smaller scale features than the metamorphic lobes, being more similar to recent terracettes.

Fabric studies of the risers of 4 granite terraces showed fabrics developed almost at right angles to the direction of maximum slope, consistent with an origin by a flow mechanism.

The scarcity of terraces in the granite and metamorphic areas suggests that uniform sheet flow of the coarse debris mantle has not been usual, but that movement was largely restricted to zones of relatively rapid flow, forming the commonly occurring lobes.

CHAPTER 7

Gliding Boulders

Introduction

Individual boulders that travel downslope faster than the slope deposits upon which they rest occur under a wide range of climatic conditions. These features have been given various names (see Chapter 3) but the term gliding boulder is well established and will be used in this study to describe the frost controlled examples considered here.

Gliding boulders are recognised by their association with a certain combination of microfeatures. The relatively rapid movement of the boulders causes them to cut or plough down through the surface of the finer material upon which they rest, producing an arcuate ridge of displaced turf and soil material in front and an elongate hollow behind. Lateral turf rolls may or may not be present. Several authors have likened the features produced by these phenomena to the bow-wave and wake of a ship (eg. Galloway, 1958). The frontal ridge is commonly termed the bow-wave, and the hollow behind the boulder, the furrow. Tufnell (1972) recently adopted the terms mound and depression respectively.

Previous Work

A very comprehensive bibliography dealing with the history of the study of gliding boulders was given by Tufnell (1972), a review that contained a wide range of terms from various languages describing gliding boulders and their associated features.

Gliding boulders have rarely been examined in detail despite the fact that they occur frequently in 'mild' periglacial regions. The first descriptions and explanations were given in the early twentieth century by Scandinavian writers, but few further studies appeared until the 1950's when interest in gliding boulders increased (Tufnell, 1972). Gliding boulders have been identified widely throughout the mountains of Europe, notably in the Alps, the Appenines, the uplands of central and southern Germany, the Pyrenees and Massif Central, and in Britain, Rumania, Sweden, Norway, Czechoslovakia and Greece.
Some of the first descriptions of gliding boulders occurring upon the hills of the British Isles appeared in articles by

Hollingworth (1934, p.174) and Hay (1937, 1942). Hay referred to them as gliders or gliding blocks and stated that they were one of the most interesting phenomena on the summit land of the English Lake District. They were found to occur only above 500m a.s.l.. Their most constant feature, apart from the characteristic 'symptoms' of a frontal turf roll and a rearward furrow, was found to be their orientation lengthwise along their own furrow that was cut down the line of the principal slope. The Lake District 'gliding blocks' were found on "almost every fell possessing the requisite height and slope and of which the surface has the necessary amount of small earthy material to form a suitable soil-flow mixture". Hay concluded that "this downhill movement of blocks, suitably situated, must have been going on ever since the ice left the tops of these fells". In his second article Hay (1942) stated that the 'gliding block' had a wider altitudinal range than any of the other solifluction phenomena found on the fells, and generally occurred on slopes of about 1 in 7 (8°).

The next recorded observations did not appear for almost twenty years, until Galloway (1958) described individual boulder phenomena from the Scottish Hills. He recognised boulders that moved down the slope more slowly than the fine material upon which they rested, which piled up behind them as a rearward mound (brake blocks) and those that moved faster and ploughed down through the finer material (gliding boulders). No name was given to these features; they were referred to as 'individual boulders' (1958) and later (1961b) as 'individual block creep'. Brake blocks were identified upon the Knock in Banffshire, and gliding boulders were reported from Ben Wyvis, the lower slopes of Ben Macdui, upon White Coomb Hill in the Southern Uplands, and upon Tinto Hill. Galloway observed that gliding boulders usually occurred on steep gradients around 24°, but some were found on slopes as low as 6°, and 10° in the Southern Uplands, and were characteristically aligned down the slope. He concluded (1958, p.128) that gliding boulders were actively moving, but boulders lying more deeply did not appear to be moving so readily.

Tivy (1962) later reported, from the Lowther Hills, large blocks and stones over 23cm long that showed evidence of contemporary movement by sliding.

Active 'gliding blocks' upon the Moor House Nature Reserve in north-east Westmorland were discussed by Johnson and Dunham (1963). They were referred to as 'large' boulders of sandstone, but no dimensions were given. The boulders were reported to move during the spring thaw, when the subsoil was still frozen, normally progressing very slowly, but an exceptional movement of 1.5m in one year was recorded. Pipkrake-type ice was observed beneath boulders from September to May and it was believed that the daily melting of this ice in spring lubricated the base of the boulders.

The first study to attempt to define a list of limiting factors regarding the distribution of gliding boulders was from the Western Cairngorm Mountains of Scotland (King, 1968). They were reported to occur mostly on grassy concave slopes of 5°–30° gradient with an easterly aspect, and between 850m and 1,200m elevation. One notable exception was found at 693m on a north-facing slope. Gliding boulders were found to occur frequently in Schneeflecken (grassy areas that are the sites of late lying snow patches) along with terracettes and elongate and occasionally transverse mounds. King reported that schneeflecken did not favour any particular aspect, and ranged in elevation from 550m to 1,200m on slopes between 15° and 35° gradient.

Furrows were generally about 1m long, sometimes reaching 3.5m long. In every case the furrows were aligned in the direction of the strongest declivity, V-shaped and usually 45cm wide and a few centimetres deep at the top, widening downslope to incorporate the boulder. The boulders were nearly always elongate downslope and surrounded on three sides by a ridge. Sometimes the distribution of gliding boulders was so dense that a boulder and hollow topography was developed.

Sugden (1970a), also working in the Cairngorms, described boulders backed by grooves up to several metres in length, with a bow-wave in front. They were said to occur on slopes of varying steepness above 830m elevation, and were believed to be influenced by aspect more than any other periglacial landform. Sugden, after King (1968) believed that gliding boulders occurred almost exclusively on east-facing slopes.

Tufnell (1969) pointed out the scarcity of studies concerned with gliding boulders, although they are among the most widespread of contemporary periglacial phenomena in northern England. Gliding boulders were found to be active down to relatively low altitudes, a lower limit of 450m being reported. Other periglacial features were not found below 600m. The better developed gliding boulders occurred at around 820m on Little Dun Fell. Gliding boulders were found to range in composition and included sandstone, limestone, andesite and rhyolite. The exact form of the bow-wave was found to be dependent upon such factors as internal composition, extent of the vegetation cover, and its size. Furrows had less variable characteristics than the bow-wave: the first type was the elongate variety whose length could exceed 6m (20ft) and the second was the half bowl or niche-shaped depression. No slope angle or aspect preferences were determined for gliding boulders, but they were often found in association with small active congelifluction terraces, cryoplanation benches and nivation hollows (Tufnell, 1971). Experiments suggested a mean annual movement rate of from 1-5cm. Spring was the most favourable period for congelifluction in northern England. Although the exact mechanisms of boulder movement were unsure, the main agent was believed to be frost, assisted by temperature fluctuations, water and gravity.

Gliding boulders have only recently been recognised in North Wales. Goodier and Ball (1969) described 'gliding blocks' from the Rhinog Mountains at 700m elevation on a slope of 27^{o}. The larger of two examples was 1.6m long with a 13m furrow. Other good examples were seen at 610m on the Moelwyn Mountains, at 885m on the Carneddau Mountains and at 760m in the Glyder Mountains. Gliding boulders were believed to be stable at the present day, but the authors pointed out that this had not been proved unequivocally. Further observations of gliding boulders from North Wales (Ball and Goodier, 1970) in the Snowdon area showed them occurring above 600m. Because of their association with other frost action phenomena they were classified as features mainly due to gelifluction processes occurring during seasonal thaw. The movement mechanism was thought to be that of sliding upon unstable water-saturated or loosely-frozen ground, the block being lifted by needle ice during a freezing episode followed by a shift upon thawing. It was considered that the movements deduced from the furrow evidence could have occurred in one episode, or intermittent reactivation of movement was considered a possibility. The authors believed that the requirements for movement included a 'moderate slope', and widely scattered boulders to allow unimpeded progress of individual blocks. It was suggested that after a 'substantial' movement of undefined amount, the gliding boulders were slowed down or stopped by the bow-wave of soil or vegetation. Major movements were attributed to the period between the sixteenth and late eighteenth centuries either as one episode or periodically, but it was considered possible that some boulders were moving at the present day.

The most detailed investigation of the characteristics of gliding boulders in the British Isles was presented by Tufnell (1972). He measured a range of parameters, and presented graphical results to support his descriptions and conclusions based upon a large number of examples from northern England, and some from the Alps. This study was a significant advance upon the previous methods of generalising conclusions from a small number of observations. A further important step was the experimental recording of contemporary gliding boulder movements, which gave evidence of activity, thus putting an end to the conjecture which has existed for so long.

The Present Study

It is evident from the sparse literature upon gliding boulders in general, and gliding boulders in the British Isles in particular, that very little is known about these features. The dimensions of the boulders and their furrows, the size of their associated micro-features, their distribution with respect to slope angle and aspect, and their contemporary movement rates have been generalised by a few authors from field observations but few measurements exist to support any conclusions reached.

The present study aims therefore, to establish some basic facts about the size relationships, distribution, general characteristics and movement rates of gliding boulders, derived from extensive field measurements in both granite and quartzite terrains in the south-east Grampians. Gliding boulders were examined and measured from the Lochnagar granite and the Glenshee metamorphic areas.

Gliding boulders were observed upon the Mount Keen granite area, but they were not measured.

Measurement consisted of recording at every example, the value of each of fifteen parameters that had previously been established to summarise the main features of a gliding boulder.

The parameters selected are as follows:

Altitude	the approximate elevation above sea-level of the example.
Aspect	the orientation, with reference to magnetic north, of the slope segment upon which the example occurs.
Slope Angle	the angle of declivity of the slope segment down which the boulder is travelling.
Primary Furrow Length	the length of the furrow, in centimetres, measured from the upslope edge of the boulder, to the point where the furrow becomes unrecognisable or to a major constriction.
Secondary Furrow Length	the length of the upper section of furrow that, in some examples, continues beyond a vegetation constriction.
Size A	the longest dimension of the boulder parallel to the slope surface.
Size B	the shortest dimension of the boulder parallel to the slope surface.
Size C	the height to which the boulder projects above the ground level.
Shape	a small sketch of the plan view of the boulder to assess the range of shapes that can 'glide'.
Orientation	the orientation, with reference to magnetic north, of the longest axis of the boulder.
Deviation	the difference in angle between the slope aspect and the orientation of the boulder long axis.
Bow-Wave Height	the height above the general ground surface of the crest of the bow-wave.
Bow-Wave Length	the downslope dimension of the bow-wave.
Lithology	the type of rock of which the boulder is composed.
Vegetation	the dominant plant types growing on the slope around the gliding boulder.

Altogether 350 boulders were sampled. Of these 200 were from the metamorphic area, and 150 from the Lochnagar Massif. Processing and analysis of the accumulated data (see APPENDIX 111) has allowed various conclusions to be drawn about the nature of gliding boulders and their distribution.

Present day movement activity of gliding boulders was investigated using movement marker experiments at 9 gliding boulders in the metamorphic area and 3 in the granite area. These experiments involved the placing of wooden stakes behind the selected boulder to act as fixed reference points. Relative shifts of the boulders were checked in subsequent years. A further technique for checking the movements of gliding boulders in the recent past was devised and tested. The technique involved establishing the minimum age of the furrow at known intervals along its length, by dating woody moorland plants growing in the furrows. From these data it was possible to construct time/distance diagrams that represent the movement of the investigated boulder over time.

Study Areas

Hill slopes throughout the study area, in both the granite and metamorphic terrains, varied from almost stone-free to nearly complete cover of stones and boulders. The latter was represented by valley side or hill slope screes and boulder fields. In many areas the stones and boulders were sorted into lobes and/or terraces. Upon well vegetated slopes with a fairly even scatter of isolated stones and boulders, many individual boulders appeared to be moving down the slope under the influence of frost processes and gravity, leaving a characteristic trail or furrow behind. Not every boulder on such slopes showed evidence of movement.

Five valleys in the metamorphic area, and one valley and the Stuic corrie floor in the granite area, were selected from aerial photographs as having variable scatter of small boulders upon sloping ground. Ground checking confirmed that these areas contained many gliding boulders.

Data were gathered in four main groups. Two groups were derived from the Lochnagar granite area, and two from the Glenshee metamorphic area. One hundred boulders were sampled in the Stuic corrie of the Lochnagar Massif (map ref. NO 230855). These boulders were situated upon the flanks of the hummocky morainic deposits at the

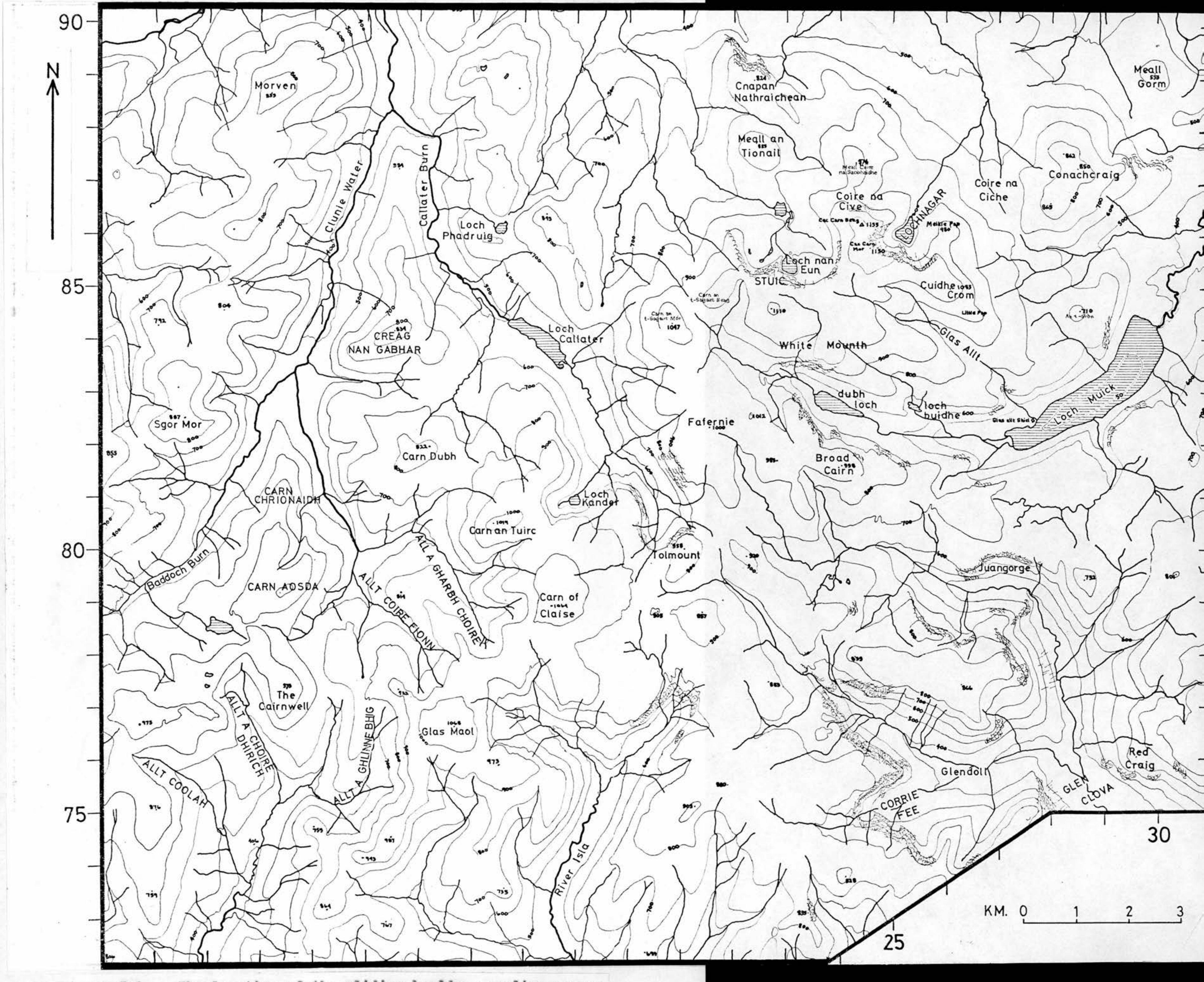


Figure 7.1 The location of the gliding boulder sampling areas

northern end of the corrie lochan.

Fifty gliding boulders occurring at the head of the Glas Allt valley of the Lochnagar Massif (NO 253848) were examined from both valley sides.

One hundred gliding boulders from the metamorphic area to the north of the Glas Maol watershed were sampled from the valleys of the Allt Coire Fionn (NO 157786), and the Allt a' Gharbh-Choire (NO 163800) and their tributaries.

A further one hundred gliding boulders were sampled from the valleys to the south of the Glas Maol watershed. These areas were the headwaters of the Allt a' Ghlinne Bhig below Meall Odhar (NO 150755), the Allt a' Choire Dhirich south of the Cairnwell (NO 130765), and the Allt Coolah (NO 124744).

Sampling Procedures

Sampling was carried out in the valley situations by walking a transect along one valley side towards the valley head, and then returning along the opposite valley side. This procedure enabled a range of possible slope aspects to be examined from a range of differently oriented valleys. Each valley side was covered in a zig-zag manner, from the stream to the top of the slope, then back down to the stream. In this way the full range of slope angles present was covered. Every boulder that was passed upon this route was checked for evidence of movement, in the form of a furrow. If a furrow was present the value of each of the fifteen parameters outlined above was recorded.

The valley sampling was aimed at examining gliding boulders from as wide a range of slope angles, and slope aspects as possible; hence it was decided not to adopt an intensive quadrat procedure upon individual valley side sections, but to spread the sampling area using the procedure outlined.

Gliding boulders from the Stuic corrie floor were sampled upon a quadrat basis, using an approximately 5m quadrat. Quadrats of 100 paces by 100 paces were measured out upon areas around the northern end of the Stuic corrie lochan. The nearest boulder lying forward of every tenth footfall was examined for evidence of gliding. If a furrow was found details were recorded.

RESULTS

Part 1: The Distribution and Characteristics of Gliding Boulders

The Distribution of Gliding Boulders

Attempts were made to determine the range of situations in which gliding boulders may develop, and if possible to define the optimum range of conditions favourable to their development.

Of the fifteen parameters measured at each site, four describe the general nature of the site. These terrain parameters are altitude, aspect of the slope, slope angle and the slope vegetation.

ALTITUDE: The sampled gliding boulders occur throughout a large altitudinal range, from 450m to 1100m (Figure 7.2).

Samples from the metamorphic area show a wide altitudinal spread as these were examined from several different valleys at varying altitudes. The lowest example identified was from the lower section of the Allt Coolah valley (NO 124742: example 181) at 450m, and the highest occurred near the head of the steep eastern tributary of the Allt a' Gharbh-Choire (NO 182801: example 060) at 930m.

Samples from the Lochnagar area reveal a marked concentration at 900-949m, reflecting the 100 samples from the floor of the Stuic corrie. The highest Lochnagar example, at about 1100m, occurred downslope of the summit col (NO 243857: example 301). The lowest granite gliding boulder was at about 840m (NO 229857: example 242).

Gliding boulders were not found to occur below 450m in northern England (Tufnell, 1970), below 500m in the Lake District (Hay, 1937), and below 600m in Snowdonia (Ball and Goodier, 1970). Lower limits of 830m (Sugden, 1970a) and 850m (King, 1968) have been suggested for the Cairngorm examples.

The lowest gliding boulder found was situated at 450m. It is anticipated that gliding boulders could develop at lower altitudes than this, but valleys at lower altitudes were not examined. An important factor that militates against finding many examples below this altitude is human interference for agriculture. The lowest example from the Allt Coolah valley was on a terrace above an area used as a picnic site, and a public lay-by and car park. Land in the valley bottoms and lower valley sides has been improved for pasture, by ploughing and stone clearance. Such activities will

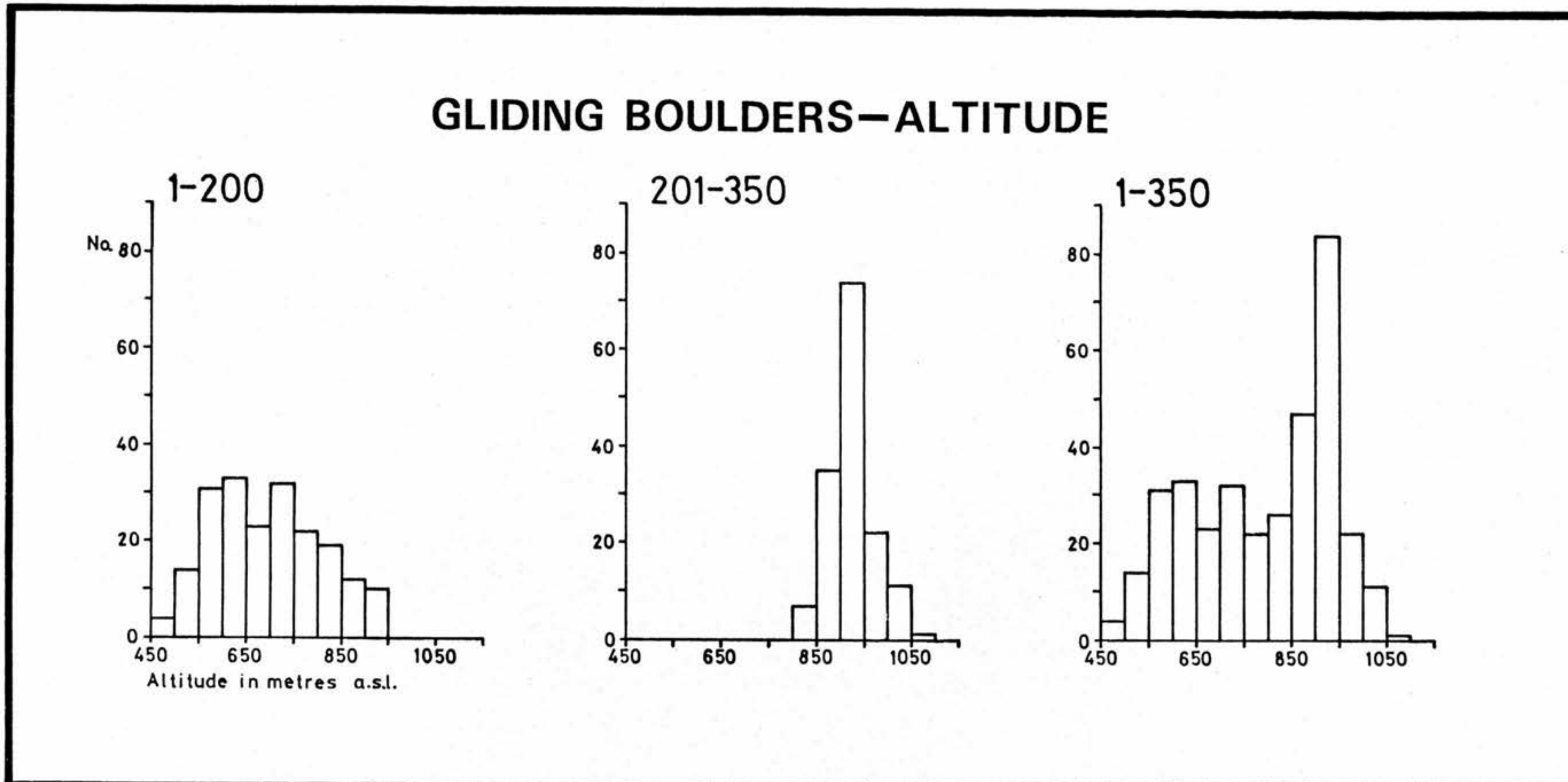

GLIDING BOULDERS—ALTITUDE
1-200
201-350
1-350
No.
80
60
40
20
0
450
650
850
1050
Altitude in metres a.s.l.

Figure 7.2

create an artificial lower limit.

Large areas of the Allt Coolah valley showed evidence of recent heather burning for grouse. This gives rise to large unvegetated patches covered with only a thin mantle of peaty soil and charred heather stems. Evidence of recent erosion scars in the peat, and the breaking up of the peaty surface in dry weather was common. This form of interference could perhaps assist gliding boulder movement by removing the restricing cover of vegetation, but could also make the identification of furrows difficult as surface wash and erosion would be increased, so accelerating the process of furrow obliteration.

ASPECT: Gliding boulders occur upon slopes of all aspects. They do not show a unique preference for slopes of any particular aspect (Figure 7.3), but two main clusters are apparent.

Almost 39% of the 350 samples occur upon slopes ranging in aspect from 20° to 140°, and about 25% occur upon slopes between 280° and 340°.

These findings differ from those of similar studies in the Western Cairngorms. King (1968) found that gliding boulders in the Cairngorms occurred mostly upon east facing slopes. Sugden (1970a) believed that gliding boulders are influenced by aspect more than any other periglacial landform, occurring almost exclusively upon east facing slopes. The present study showed that 48% of the 350 samples occurred in the eastern sector (between 0° and 180°), 33% occurring within 45° of due east, between north-east and south-east (45° to 135°). A mean value for the aspect of 185.0° reflects the relatively even distribution between the western and eastern sectors, and a large standard deviation of 109.6° demonstrates the wide dispersion of the samples.

An even distribution with regard to aspect is apparent from the Lochnagar examples (Figure 7.3 - 201-350). These samples were situated around the flanks of almost circular morainic mounds in the Stuic corrie and around the bowl shaped head of the Glas Allt valley. Such a situation presents an almost full range of available aspects, from 0° to 360°. The results show that gliding boulders in this area were not controlled by aspect.

The examples from the metamorphic area are also distributed

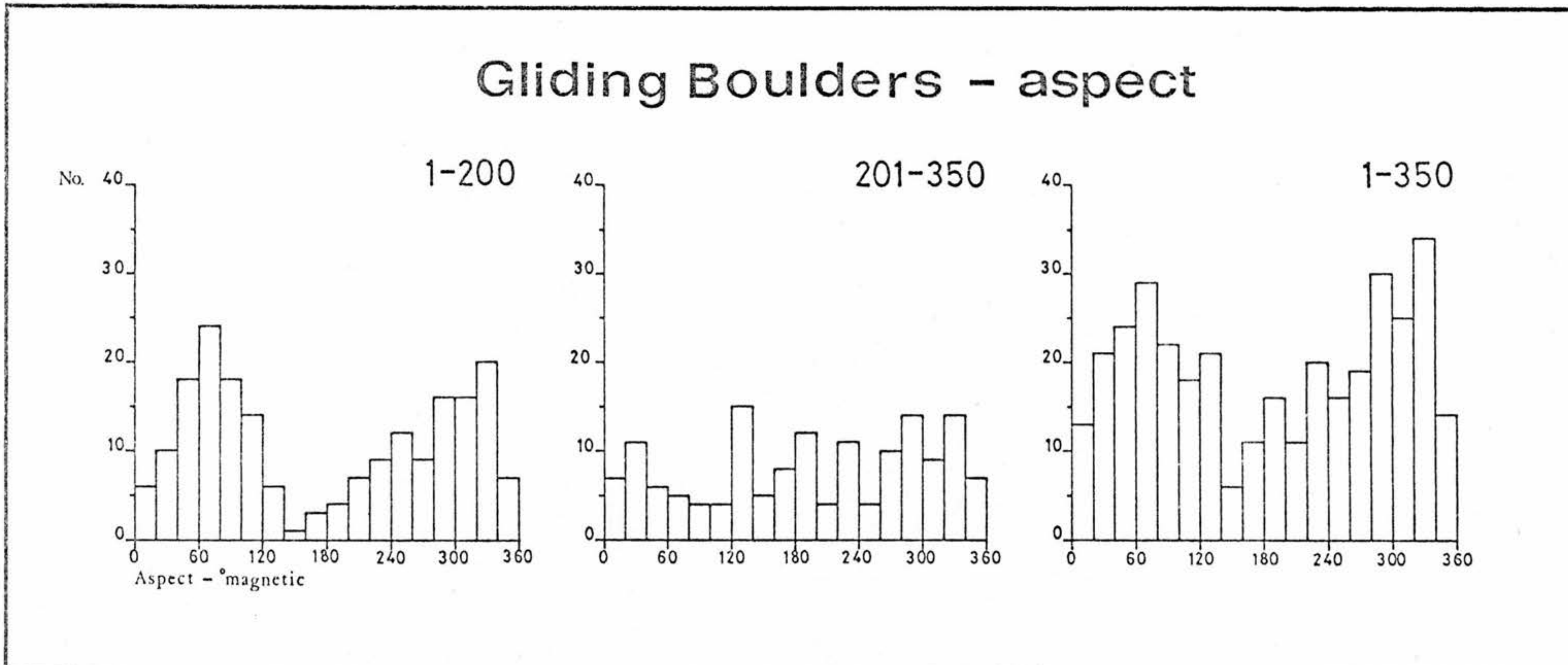

Gliding Boulders - aspect
No.
1-200
201-350
1-350
Aspect - °magnetic
0
10
20
30
40
0
60
120
180
240
300
360

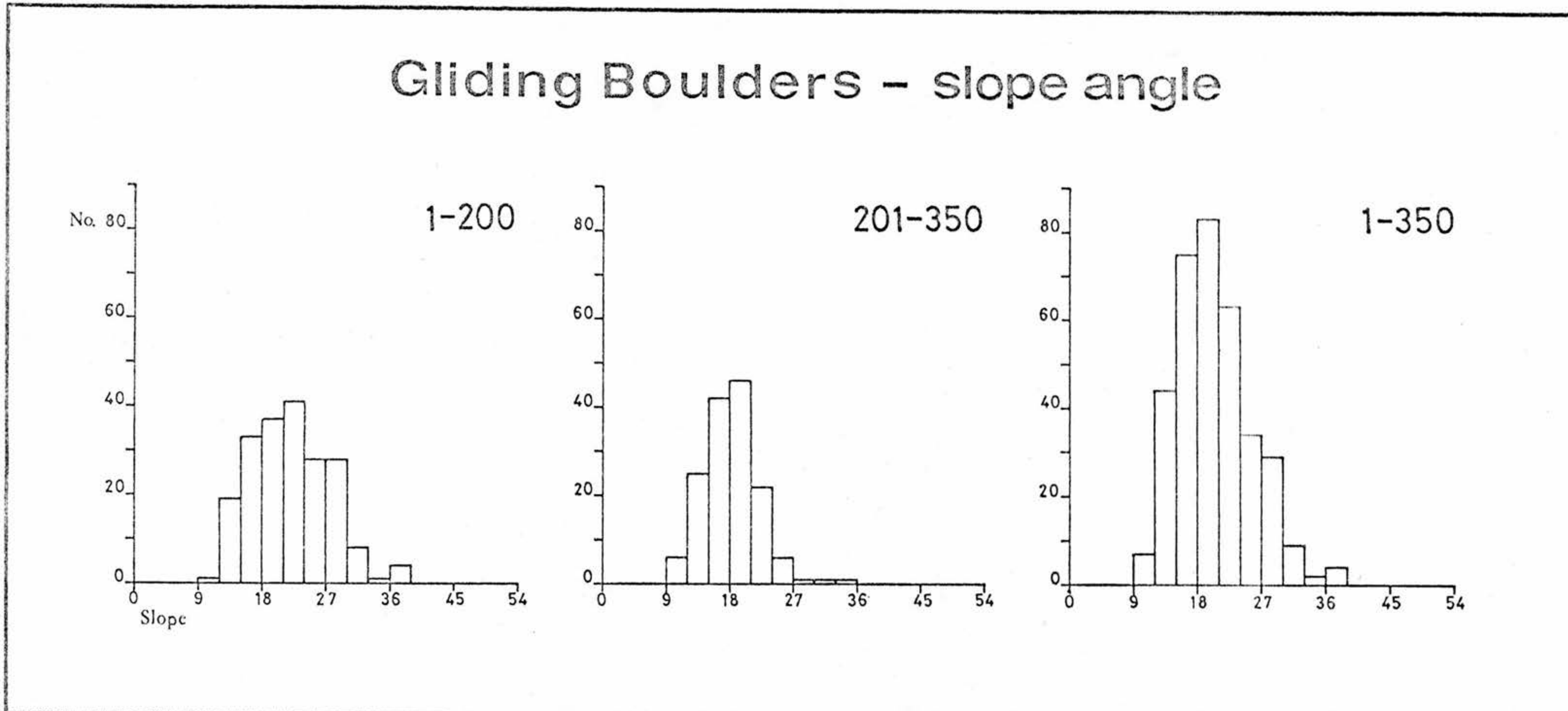
Figure 7.3

throughout slopes of all aspects, from 0° to 360°, but two marked groupings are evident (Figure 7.3: 1-200). Of the 200 observations, 37% occur between 40° to 120°, and 26% occur between 280° to 340°. One possible explanation of this clustering is that it perhaps represents the available aspects within the valley sampling situations. Sampling from two opposing valley sides would result in two groups of results, differing by about 180°. If several valleys had similar orientations then the clustering of results would reflect only the dominant aspects within the sampling areas. This problem was borne in mind when the valleys were selected initially. All the valleys examined have different overall orientations, each has marked changes of direction along it's length and several have large and small tributary valleys, all of which were sampled.

To test the hypothesis that the aspect groupings could be a direct result of the restrictions imposed by the sampling areas, the valleys were examined upon the Ordnance Survey 1:10,000 maps and the relative frequency of available slopes of different aspects was estimated. The relative percentage frequencies are shown graphically in Figure 7.5, which also shows the aspect results (from Figure 7.3: 1-200) for comparison.

The two sampled distributions were compared statistically using the Kolmogorov-Smirnov non-parametric test (Siegel, 1956), which indicates that the two populations are not statistically distinct at the 90% confidence level. From this result it is concluded that the observed clusterings of metamorphic gliding boulders upon slopes with aspects ranging from 40° to 120°, and 280° to 340°, reflect the dominance of slopes between these two aspects within the valley situations studied. Thus, it appears that gliding boulders do not favour slopes of any particular aspect, or range of aspects, but can be found in similar concentrations upon slopes of all aspects.

<u>SLOPE ANGLE</u>: The survey revealed that gliding boulders in the study area can develop upon slopes between the gradient limits of 9° and 38° (Figure 7.4). These results indicate the range of slopes upon which gliding boulders were found. It is possible that they are developed elsewhere in the area upon lesser and steeper slopes. It appears that the most favourable gradients lie between narrower limits. Thus 95% of the 350 gliding boulders sampled occur on



Gliding Boulders - slope angle
1-200
201-350
1-350
No. 80
60
40
20
0
0
9
18
27
36
45
54
Slope

Figure 7.4

slopes between 11° and 29°, and 59% occur on slopes with gradients between 11° and 20°. The mean slope was calculated as 19.9°, with a standard deviation of 5.2°.

Tufnell (1972) reported that of 500 gliding boulders sampled from the Moor House Reserve, a little over 85% were found to occur on slopes of 10° to 29°, with a mean calculated slope angle for the complete sample of 18.1°. Similar work in the Alps by Furrer (1965a - reported in Tufnell, 1972) indicated that from a survey of 120 gliding boulders, 85% were developed upon slopes of from 9° to 32°. These similar results from detailed work in three different upland areas suggest that the optimum gradients for gliding boulder development be between the limits of 10° to 30°, with an average of around 18° to 20°.

Gliding boulders were found in the Western Cairngorms upon slopes of 5° to 30° (King, 1968) and in the Southern Uplands on slopes around 24°, but some occur on slopes as low as 6° to 10° (Galloway,1958). Examples in the Lake District were found to be best developed upon slopes of around 8° (Hay, 1942).

One important problem that arises, and that was considered by Tufnell (1972, p.265) is whether the results merely represent the most frequently occurring slope angles in the areas examined. The results of the present study, giving a range of optimum gradient values very similar to those determined by Tufnell and Furrer from different areas, would seem to emphasise the slope angles most favourable to the development of gliding boulders, rather than the most frequently occurring slope angles.

Sampling in the present study was carried out on hill and ridge tops and broad convex summit areas, and also on the almost level areas beside streams. At the other extreme the valley side slopes often graded into steep scree covered side slopes or free faces. Hence a wide range of available slope angles was present in the metamorphic valleys. In very few cases were gliding boulders found near any of these slope facets, but they proliferated in the mainly concave 10° to 30° mid slope situations.

Slopes of about 40° to 45° gradient and above were characterised by terracetting of the regolith, slope failure scars, screes and bedrock projections. Boulders in these situations would be more likely to move by rolling or slipping at a rate comparable with the underlying material, than to move relatively more rapidly by gliding. The unvegetated nature of the whole of, or sections of, these high angle slopes would also tend to operate in favour of an equally rapid movement of the finer material that on lower angled slopes is bound by the vegetation layer. On lower angled slopes gliding boulders are less assisted by gravity, and so would require more severe conditions to move their large mass against the retarding effects of the coarse regolith and the frequent woody moorland vegetation.

In an attempt to resolve this speculation, a procedure was devised to accumulate a sample of slope angles from the two main sampled areas to compare with the gliding boulder slope angle results. The method involved laying a numbered grid over each of the areas from which the field data were gathered. Boundaries were drawn for each area to contain the investigation within the exact areas covered during the field search. Using a table of random numbers (in Hoel, 1971, pp. 398-399), grid intersections were located at which the slope angle upon the map was calculated. The same number of random slope samples was taken from each sampling area as the number of gliding boulders measured in that area. Thus a comparison could be made between the results of sampling the slopes upon which a certain number of gliding boulders occurred, with the results obtained from taking the same number of randomly selected slope angles from the same area.

The results of the random slope sampling exercise are illustrated in Figure 7.5, accompanied by the slope angle results from the two gliding boulder field samples (from Figure 7.4: 1-200 and 201-350). Statistically (Kolmogorov-Smirnov) the two pairs of populations are different at the 99.9% confidence level. From this finding it is concluded that the gliding boulder field sampling results indicate the slope angles that, in these areas at least, are best suited to gliding boulder development, and do not simply express the frequency distribution of slope angles within the sampling areas.

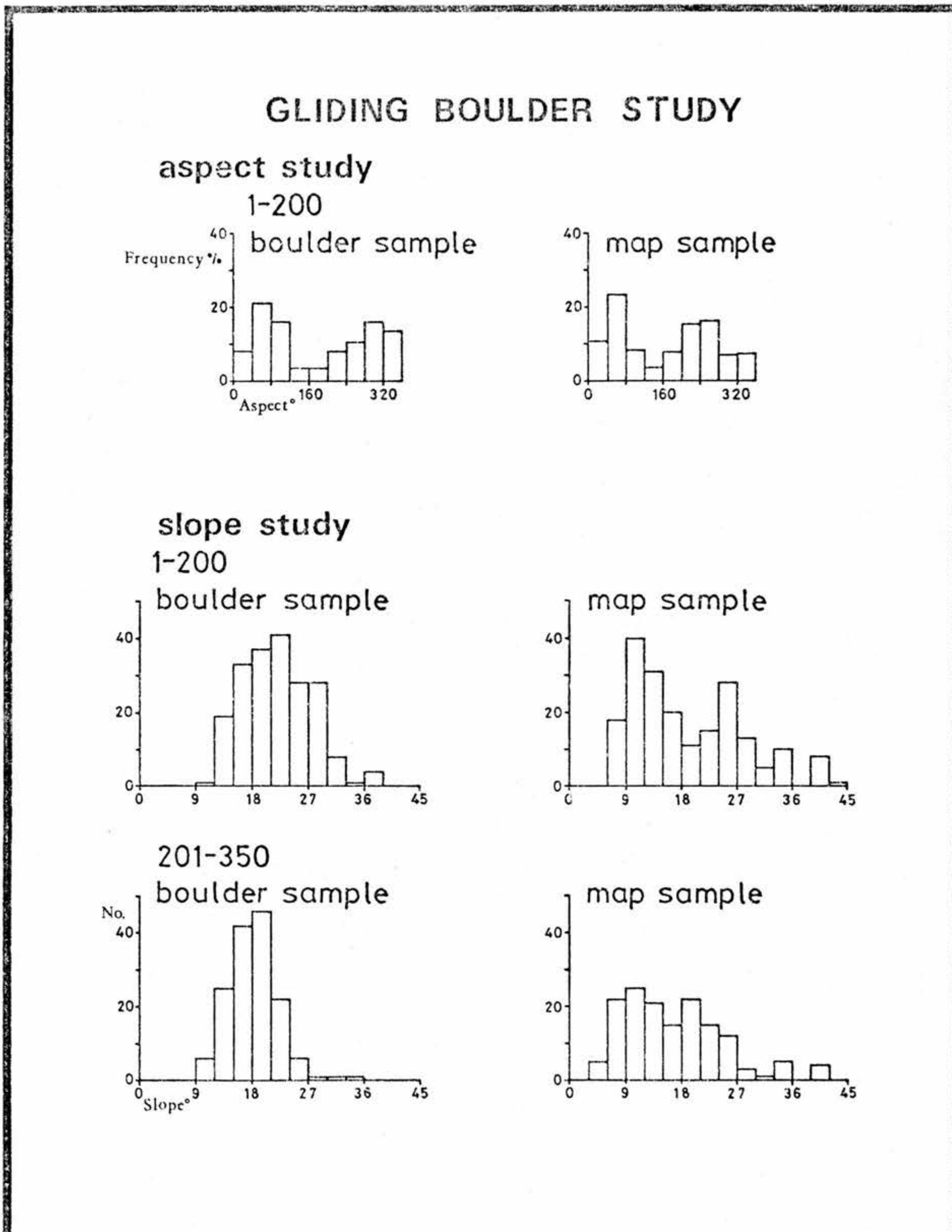

GLIDING BOULDER STUDY
aspect study
1-200
boulder sample
map sample
Frequency %
Aspect°
slope study
1-200
boulder sample
map sample
201-350
boulder sample
map sample
No.
Slope°

Figure 7.5

SLOPE VEGETATION: The vegetation of the south-east Grampian study area consists of a coarse moorland variety, containing many woody-stemmed plants and coarse grasses of a tufted habit.

About 40% of the 350 samples were situated upon slopes covered with a vegetation which consisted dominantly of grasses. In the metamorphic and granite areas Vaccinium myrtillus was the characteristic sub- or co-dominant cover species, and sometimes replaced the grasses as the dominant in areas through which gliding boulders were travelling. Heather (Calluna vulgaris) combined with vaccinium was common among the grasses on the slopes of the granite area. In some instances in the granite area, the furrows of gliding boulders extended through continuous mats of vaccinium (Photograph 7.B). Often mats of vaccinium extended up onto the boulder itself (Photograph 7.D).

Gliding boulders have been largely described as occurring upon grassy slopes where they are believed to be best developed (eg. King, 1968; Tufnell, 1972). The present survey has shown that they can develop upon slopes that support a vegetation consisting dominantly of grass, or vaccinium, or heather, or mixed communities of these three species, combined in varying proportions.

Dahl's observations (1956, p.77) in the Rondane district of Norway led him to conclude that 'solifluction' prevents the growth of Vaccinium myrtillus. Such a relationship has been noted by other authors (eg. Williams, 1957a, p.45, 1959a, p.7; Kallander, 1967, p.36) during investigations of solifluction phenomena. The presence of vaccinium upon a slope would seem to indicate, therefore, that the slope regolith is fairly stable at the present time. Because many of the gliding boulders in the present sample were travelling down slopes that were vegetated with a plant assemblage which often comprised a large proportion of vaccinium it seems likely that the gliding boulders will be only minimally affected by geliflual (soliflual) movements of the regolith.

The Characteristics of Gliding Boulders.

The four terrain parameters, discussed above, indicated the nature of the slopes upon which gliding boulders occur. Eleven further parameters were established to describe the main characteristics of gliding boulders and their associated micro-features.

The length of the furrow produced by the movement of the boulder was measured. This was generally found to consist of two sections, so two readings were taken (see below). Measurements were made of the length and height of the bow-wave, and of the three main dimensions of the boulder. A compass reading was taken of the orientation of the boulder long axis, from which, knowing the aspect of the slope, the angle of deviation of the boulder long axis from the true downslope direction could be calculated. Sketches were made of the plan view of each boulder in order to establish a catologue of the forms of boulder which can glide. Finally the lithology of the boulder was determined.

The Furrow: The furrow behind a gliding boulder is its most diagnostic feature. It is the presence of a linear depression upslope of a boulder that causes it to be recognised in the first instance (eg. Photographs 7.3 and 7.4). Gliding boulders travel downslope faster than the slope deposits upon which they rest, with the result that a linear depression is cut during their downslope progress. Brake blocks on the other hand have a linear depression on their downslope side.These blocks are travelling downslope more slowly than the slope deposits upon which they rest; hence, the regolith flows past them, banking up a 'bow-wave' type feature against their upslope edge and leaving a depression downslope. No brake blocks were seen in the present study area.

The length of the furrow represents the minimum distance over which the gliding boulder has travelled. A number of processes could possibly operate to obscure or obliterate the furrow. Gelifluction and soil creep processes would progressively level out the furrow by depositing material within the furrow and by slowly degrading the sharply defined furrow walls until the furrow cross profile is so shallow it is indistinguishable from the surrounding irregular slope. The development of vegetation in the furrow and the extension of plants from the surrounding slope into the furrow obscure the outline of the furrow.

As indicated in the slope vegetation section, the gliding boulder slopes are frequently characterised by a vegetation community consisting of a large proportion of Vaccinium myrtillus which, it has been shown, is prevented from growing upon active solifluction slopes. It seems reasonable to suppose that these results from Norway and Finmark (Dahl, 1956; Williams, 1957a, 1959a; Kallander, 1967) apply equally to the Scottish situation, that is, vaccinium growth would be prevented by gelifluction movement in any type of periglacial climatic environment. The presence of actively growing Vaccinium myrtillus upon these slopes suggests that the slope materials themselves must be relatively stable. Large scale gelifluction movement cannot, therefore, be expected to account for furrow obliteration. Small scale gelifluction, such as the degradation of the furrow walls to cause a general levelling out of the profile is the most likely mechanism.

Tufted and woody vegetation types are also responsible for obscuring the outline of the furrow. The mat-like vaccinium, and calluna branches encroach upon the edges of the furrow, finally establishing growing plants on the furrow floor and slowly concealing the furrow under a mass of woody stems (eg. Photograph 7.5). One particular feature of the furrow vegetation soon became apparent. Behind each boulder the furrow floor was usually vegetated with low growing plants, which gave way up the furrow to small, low plants more similar to the slope vegetation. At a certain point upslope in many furrows, a large tuft of vegetation was established, either rooted entirely upon the furrow floor, or encroaching onto the furrow floor from the adjacent slope (Photograph 7.2) and effectively causing a constriction in the furrow. Behind, (upslope of) this tuft, the furrow usually continued for a certain distance, but much narrower and more vegetated, and generally less distinct, finally fading imperceptibly into the surrounding slope. The section of the furrow below this constriction was termed the PRIMARY FURROW, and the section above the SECONDARY FURROW.

The primary furrow length was taken to be the distance from the upslope edge of the gliding boulder to the downslope edge of

PHOTOGRAPH 7.1 Granite gliding boulder No.253 showing the deep furrow immediately upslope of the boulder, and the three-stage furrow. The rucksack is 45cm high.

PHOTOGRAPH 7.2 Granite gliding boulder No 253. Stage 1 of the furrow is concealed behind the boulder. Stage 2 finishes just behind and to the left-hand of the rucksack where a thick clump of Vaccinium myrtillus projects into the furrow. The second stage of the furrow is asymmetrical in cross-profile, terminating with its right-hand edge below the rucksack, but the former outline of the wider furrow can be seen beyond, and to the right of, the rucksack. The rucksack is 45cm. high.

the vegetation tuft beginning the constriction, or in the case of furrows with no constricted or secondary furrows, to the point of final disappearance of the furrow. Results of the primary furrow measurements are shown in Figure 7.6. Above this point the continuing secondary furrow, where present, was measured from the downslope edge of the constricting tuft until the final disappearance of the furrow, the approximate position at which the furrow became undistinguishable from the surrounding slope. The lengths of the secondary furrows are shown in Figure 7.6, as are the cumulative (primary plus secondary) lengths of each furrow. Only 25.5% (51) of the 200 metamorphic gliding boulders had secondary furrows developed, and 42.6% (64) of the granite (150) samples.

Granite gliding boulder No. 253 (Photographs 7.1 and 7.2) had a specially well developed secondary furrow and is described here to illustrate the phenomenon. This boulder is situated on the flanks of a knoll, upon the floor of the Stuic corrie of Lochnagar (approximate map ref. NO 233854). The primary furrow was slightly narrower than the width of the boulder, and extended upslope for 217 cm. to a dense growth of bushy vaccinium (illustrated in Photograph 7.2, immediately behind the rucksack). Above this vaccinium tuft the secondary furrow extended for a further 169 cm and was considerably more constricted. In addition a third section of the furrow was identified immediately behind the boulder, which extended upslope for 35 cm. This section was as wide as the boulder and so it is considered that this section represents the most recent phase of movement. It was vegetated with short mossy heath type vegetation, in contrast to the rest of the furrow which had a cover of short vaccinium. The present day movement of this boulder was investigated over a three year period. Results of the survey are reported in the Gliding Boulder Movement Section.

Usually there is not such a distinct zone of wide furrow behind gliding boulders, and such a well marked sectioning of the primary furrow. Generally, furrows were seen to constrict gradually from a maximum width immediately behind the boulder until either the tuft at the beginning of the secondary furrow

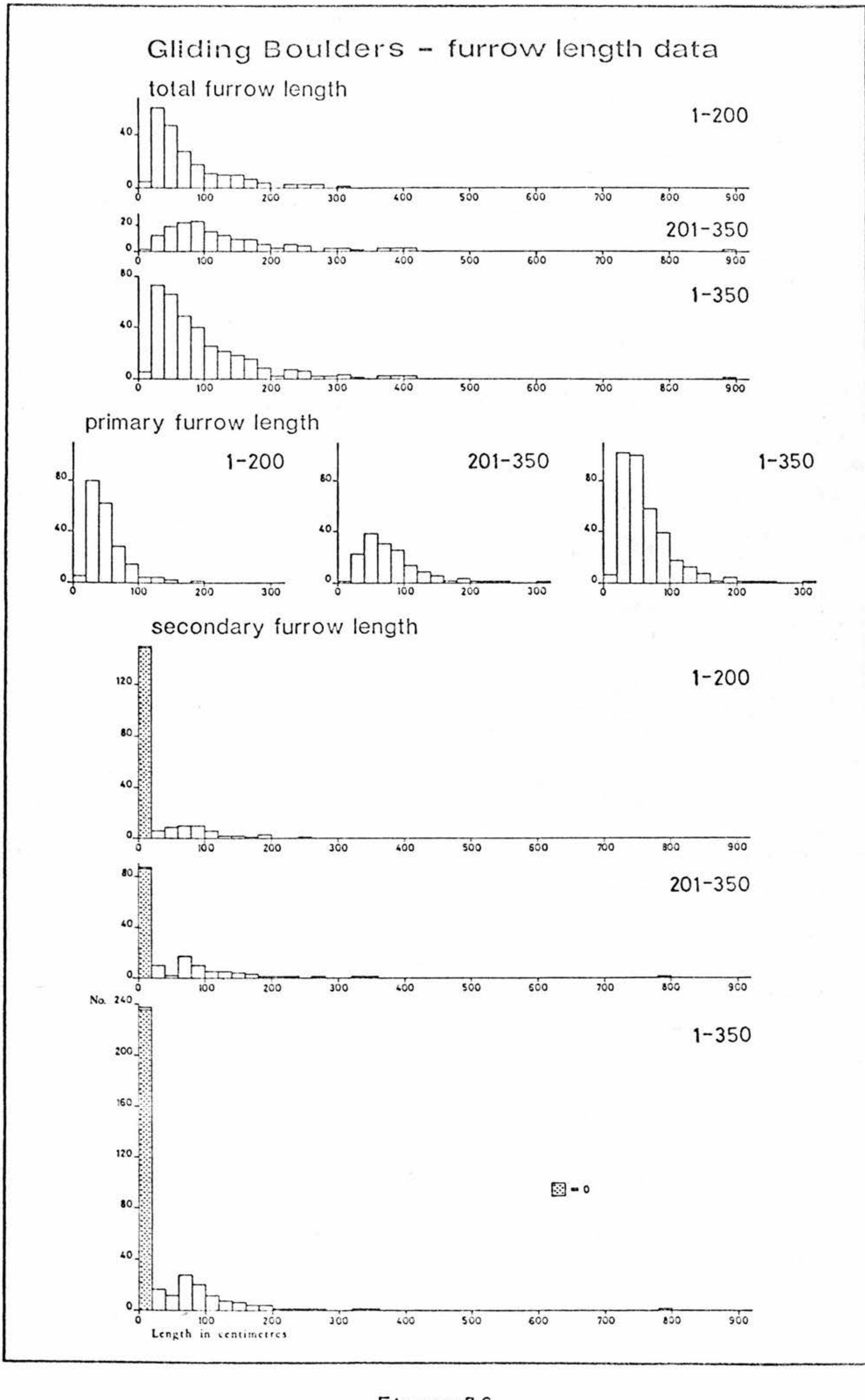

Gliding Boulders - furrow length data
total furrow length
1-200
201-350
1-350
primary furrow length
1-200
201-350
1-350
secondary furrow length
1-200
201-350
1-350
No.
= 0
Length in centimetres

Figure 7.6

is reached, at which the furrow suddenly constricts, or until it finally becomes so shallow (Photographs 7.3 and 7.4) or so narrow (Photograph 7.5) that it is indistinguishable from the surrounding slope surface.

Another characteristic feature of the furrow is the existence behind most of the gliding boulders sampled, of a short unvegetated gap between the soil of the furrow floor and the upslope edge of the boulder. This is not usually visible unless the furrow vegetation is pushed aside. The zone is usually less than about 3 cm wide and extends under the boulder, giving the impression that the base of the boulder is slightly below the soil surface and recent forward movement of the boulder has left this vegetation free gap upslope. That such a gap can exist emphasises the contention that the regolith, in areas where these gliding boulders occur, is not subjected to large or frequent downslope movements.

The furrows behind gliding buulders in the metamorphic area were generally shorter than those behind granite gliding boulders. Primary furrow lengths behind the 200 metamorphic samples ranged from 15 cm to 196 cm, with a mean length of 49.96 cm (standard deviation 27.3 cm). Primary furrow lengths behind the 150 granite boulders ranged from 13 cm to 307 cm, with a mean length of 78.39 cm (standard deviation 45.90 cm).

The bulk of the metamorphic samples (68.5%) show primary furrow lengths of 21-60 cm (Fig 7.6), and the bulk of the granite samples (77.3%) had primary furrows of 21-100 cm long. The sharp rise in representation at 21 cm (ie. the scarcity of furrows below 20 cm long) is considered to be a result of the field work procedure rather than the lack of furrows of up to 20 cm. The sampling procedure involved identifying furrows behind boulders whilst walking a transect. Such a method would allow only the longer, more obvious furrows to be noticed. The frequent occurrence of dense and branching vegetation around and behind the boulders would obscure such short furrows.

Short furrows were described as niche furrows by Tufnell (1972). No limits were given at which his niche-type becomes an elongate-type. The present work suggests that 20 cm would be a

PHOTOGRAPH 7.3 Granite gliding boulder No.304. Illustrating a rectilinear furrow cross-profile, and a lower straight furrow with a curved upper section. NOTE: the boulder under the Vaccinium to the right-hand edge of the gliding boulder, causing it to be deflected from its course; also the boulder in its new path.

suitable division, as below this length the furrows tend to be easily obscured or ignored, but above this they are readily recognised.

Only one of the granite gliding boulders in the present granite sample had a primary furrow of less than 20 cm, and only 4 of the metamorphic examples. The apparently greater frequency of furrows of less than 20 cm length in the metamorphic area is perhaps a result of the fact that slopes in the metamorphic area were more commonly covered with grass, making short furrows more evident. Such short furrows are probably far more common than the present results indicate.

A total of 51 metamorphic gliding boulders was observed to have secondary furrows. These ranged from 17 to 242 cm in length, compared with a range of 15 to 782 cm for the 64 granite examples. Almost 59% of the secondary furrows in the metamorphic area were below 90 cm, and only 1 example was longer than 200 cm. Similarly 58% of the secondary furrows in the granite area were less than 90 cm long, but 5 were longer than 200 cm.

Such secondary furrows do not appear to have been identified elsewhere. Tufnell (1972, p.248) discovered a furrow, behind a gliding boulder in northern England, which consisted of 2 halves, separated by a gap of 1.3 m. He also described an example from the Swiss Alps where the lower section had a fairly constant width and the upper section was constricted, but by geliflual movements and not by vegetation as in the present study area.

The total furrow lengths of the present examples ranged from 15 to 317 cm in the metamorphic area (mean 71.93 cm), from 13 to 888 cm in the granite area (mean 127.73 cm). These results are similar to those recorded elsewhere in the British Isles. Furrow lengths have been observed as reaching over 300 cm in northern England (Tufnell, 1972) and up to 350 cm in the Western Cairngorms (King, 1968). One example was recorded in North Wales with a furrow length of 13 m (Goodier and Ball, 1969). The lengths of composite furrows, that is those with a primary and secondary section, ranged from 15 to 317 cm in the metamorphic area, and from 60 to 888 cm in the granite area. In the metamorphic area 16 of the 51 composite furrows were less than 100 cm long, 28

PHOTOGRAPH 7.4 Granite gliding boulder No 310. Illustrating a straight furrow, with a shallow, curved cross-profile. Also note the Vaccinium mat growing up onto the boulder.

PHOTOGRAPH 7.5 Granite gliding boulder No 316 Illustrating a large gliding boulder, 124/56/39cm, with a deep V-shaped furrow. The furrow constricts gradually uphill, and also shallows in depth uphill. The rucksack is 45cm high.

were between 100 and 200 cm long, and 7 were longer than 200 cm. Equivalent figures for the 64 granite gliding boulders with composite furrows were 12, 32 and 20.

Furrows were usually fairly straight in plan and followed the direction of maximum slope (Photograph 7.3 and 7.4). Exceptions to this general rule were rare. Some furrows showed slight changes of direction over irregular terrain where they followed declivities of the microtopography, or were deflected around projections (Photograph 7.3). Tufnell (1972, pp. 246-247) classified furrows as straight, angular, curved or winding. Unfortunately no figures were presented to illustrate the relative frequency of each type in this study area.

The cross-sectional form of the furrows was difficult to establish due to many factors including the coarse nature of the vegetation and the presence of vegetation tufts which tended to obscure the ground form. The majority of furrows were roughly rectilinear in profile (Photograph 7.3), comprising a flat floor with low but steeply rising sides. Many furrows had a curved cross-profile. Transitional forms were very common, a rectilinear or nearly rectilinear (depending upon the shape of the gliding boulder) cross-profile merging upslope into a degraded and more rounded section, or even a constricted V-shaped section (Photograph 7.5). No V-shaped furrows were observed immediately behind a boulder. Tufnell (1972,p.247) identified five types of furrow cross-profile in northern England, namely trough shaped (rectilinear), parabolic (curved), U-shaped, V-shaped and complex. The most common forms were the trough shaped and parabolic making up 76% of the examples.

No figures are available for the widths of the furrows, because furrows were always variable in width and tapered upslope, and furrow margins were indistinct and difficult to locate with certainty. A more useful measure would be the rate of change of furrow width upslope, if a general procedure could be established for locating furrow margins. In most cases the furrow was widest at its lowest point, immediately behind the boulder, a fact noted by King (1968) in the Western Cairngorms. In some cases a widening of the furrow upslope was evident, suggesting that the boulder had temporarily rotated to present a wider section.

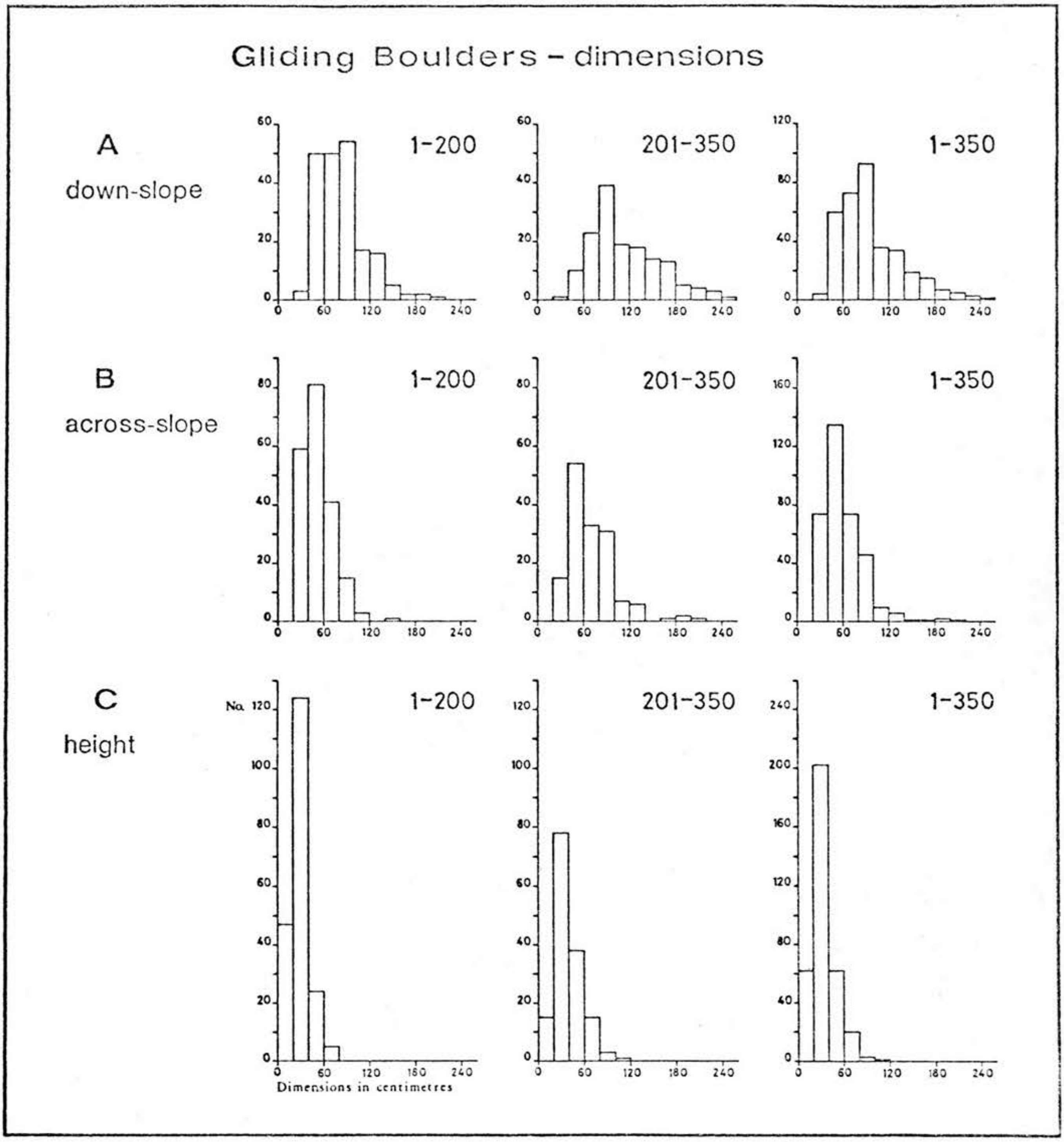
Similarly the depth of the furrow was not recorded as no suitably reliable method of meaningful measurement could be established. Furrow depth tended, in general, to be deepest immediately behind the boulder, and to shallow upslope. This impression was often accentuated by the dense growth of woody plants higher up the furrow floor. The irregular ground through which the furrow passed also made the selection of a suitable reference level difficult. Some method of recording the rate of change of depth of the furrow upslope would provide a useful addition to a rate of change of width study.

The furrow of a gliding boulder has been shown to be potentially a very variable feature, whose development is subject to the interplay of several factors, including the shape and size of the boulder, its speed and orientation of movement, the rate of gelifluał movement of the slope regolith and the type and characteristics of the slope vegetation. The furrow is the only indication, apart possibly from the presence of a bow-wave, that the boulder has moved down over the slope deposits. In the absence of any movement measurements, it is the length of the furrow that gives the only indication of the boulder's ability to move and overcome the resistance of the slope deposits and vegetation, and hence of its rate of movement. These correlations are attempted in a later section.

Boulder Size: The three main axes of each gliding boulder were measured. The longest axis parallel to the slope surface, the shortest axis parallel to the slope surface, and the height of the boulder above the ground were recorded.

Most of the boulders had very irregular shapes; consequently the recorded dimensions do not give a very clear picture of the boulder shape, but indicate the approximate volume.

Boulders in the metamorphic area were generally smaller than those in the granite area. This results from the difference in the nature of the rock types, namely their different modes of jointing and joint spacing, and the difference in susceptibility and response to weathering. The quartzites and schists of the Glenshee area are much more closely jointed than the granite



Gliding Boulders - dimensions
A
down-slope
B
across-slope
C
height
1-200
201-350
1-350
No.
Dimensions in centimetres

Figure 7.7

rocks of the Lochnagar Massif, and so produce smaller joint-bounded blocks.

The metamorphic gliding boulders ranged from 38 to 215 cm long, 20 to 150 cm wide and from 9 to 69 cm high. Granite boulders ranged from 39 to 240 cm long, 23 to 200 cm wide and 7 to 102 cm high. Smaller boulders predominate; large boulders were rare (Figure 7.7). Thus 78.5% of the metamorphic gliding boulders were less than 100 cm long, 90.5% were less than 80cm wide, and 85.5% were less than 40 cm high (97.5% were less than 60 cm high). In contrast, only 48.5% of the granite gliding boulders were less than 100 cm long, 68% less than 80 cm wide and 62% were less than 60 cm high.

The average dimension of a metamorphic gliding boulder was found to be 82.5 x 51.7 x 28.3 cm with standard deviations of 30.4, 19.5 and 11.5 cm respectively. Granite gliding boulders averaged 113.5 x 70.0 x 38.3 cm with standard deviations of 45.0, 31.0 and 17.9 cm respectively. Both these categories of average boulders are larger than those examined in northern England by Tufnell (1972, p.245), which were 65 x 49.5 x 16.3 cm average dimensions. Some boulders were wider than 150 cm and so wider than some of the present metamorphic gliding boulders, but no ranges were given. The average dimensions of gliding boulders from the Swiss Alps (Tufnell, 1972) were 146 cm long x 116 cm wide, no heights being given. Both lengths and widths of some of these boulders were greater than 300 cm. The present boulders are therefore smaller than some Alpine examples, but large in comparison to the northern England examples, and those found in the Rhinog Mountains of North Wales (Goodier and Ball, 1969) where the longest recorded example was 160cm long, only 66% the length of the longest granite example from the present study.

Boulder Shape: Gliding boulders varied very widely in shape between different examples; conversely, a wide variety of boulder shapes can move by gliding. The shapes, in plan view, encountered during the field sampling were sketched to assist a later classification of shapes.

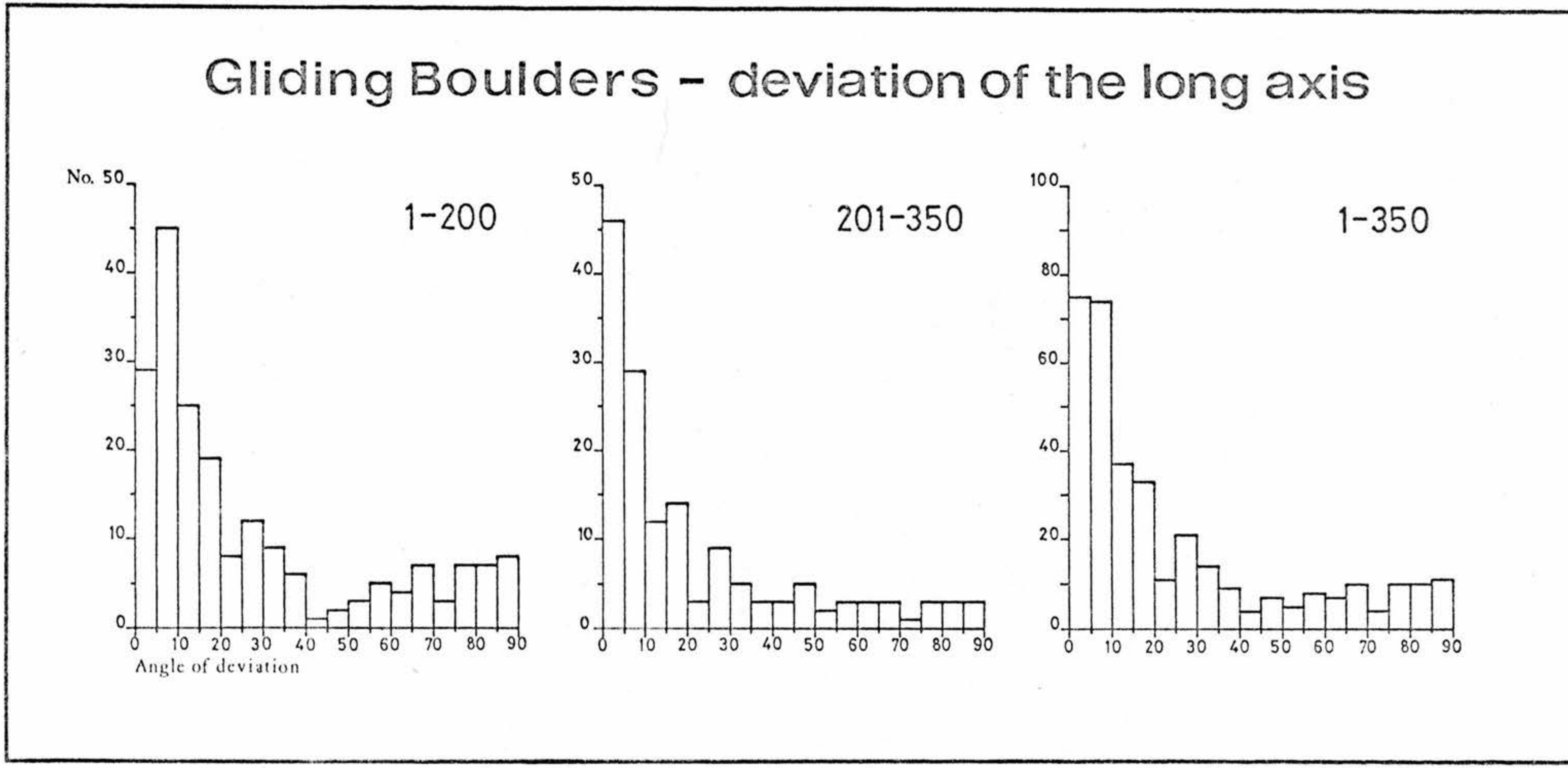
Tufnell (1972, p.242) suggested that the optimum shape for movement by 'ploughing' is a rectangular prism. The validity of this assumption, in the present case, was tested by calculating the number of boulders in the two samples whose shape approached a rectangular prism. Of the 200 metamorphic boulders 109, or 54.5% broadly approached this form, as did 59, or only 39.3% of the 150 granite samples. This approach indicates that the rectangular prism is not the dominant shape of gliding boulders in this area. The suggestion that rectangular prisms are the optimum shapes as regards ability to 'plough', that is they leave the longest furrows (move at the fastest rate), is examined in a later section.

The remaining boulder forms were difficult to classify, but five general categories are apparent. These are ellipsoidal, a triangular ground plan with a plane upper surface, a triangular prism (standing up like the roof of a house), a square-based pyramid and finally a category of irregular shapes comprising roughly diamond-shaped, coffin-shaped, curved and highly irregular forms.

Of the remaining 91 metamorphic gliding boulders 40 were irregular, 21 triangular, 20 had the form of a triangular prism and 2 were pyramidal. The remaining 91 granite gliding boulders were classified as 43 irregular, 23 triangular, 8 triangular prismatic and 1 was pyramidal.

The shapes reflect the nature of the rocks and the effects of weathering, but the results of the shape studies indicate that almost any shape of boulder can glide, that shape does not in itself prevent gliding. This shape classification is of course only concerned with the above ground portion of each boulder, no account having been taken of the form of the under-surface of each boulder. This may be the most important characteristic of a boulder in terms of its ability to glide.

Boulder Alignment: The orientation of the long axis of each gliding boulder was measured using a magnetic compass. This measure allowed the angle of deviation of the boulder long axis from the direction of maximum slope, represented by the aspect, to be calculated. The angle of deviation was calculated for each example, and the results plotted in 5^{o} categories from 0^{o} to 90^{0} (Figure 7.8).



Gliding Boulders - deviation of the long axis
No. 50
40
30
20
10
0
1-200
0 10 20 30 40 50 60 70 80 90
Angle of deviation
50
40
30
20
10
0
201-350
0 10 20 30 40 50 60 70 80 90
100
80
60
40
20
0
1-350
0 10 20 30 40 50 60 70 80 90

Figure 7.8

It seems to be generally accepted that gliding boulders tend to be aligned with their long axis almost parallel to the direction of maximum slope (eg. Hay, 1937; Galloway, 1958; King, 1968). This observation was tested by Tufnell (1972), and has been examined in the light of the present results.

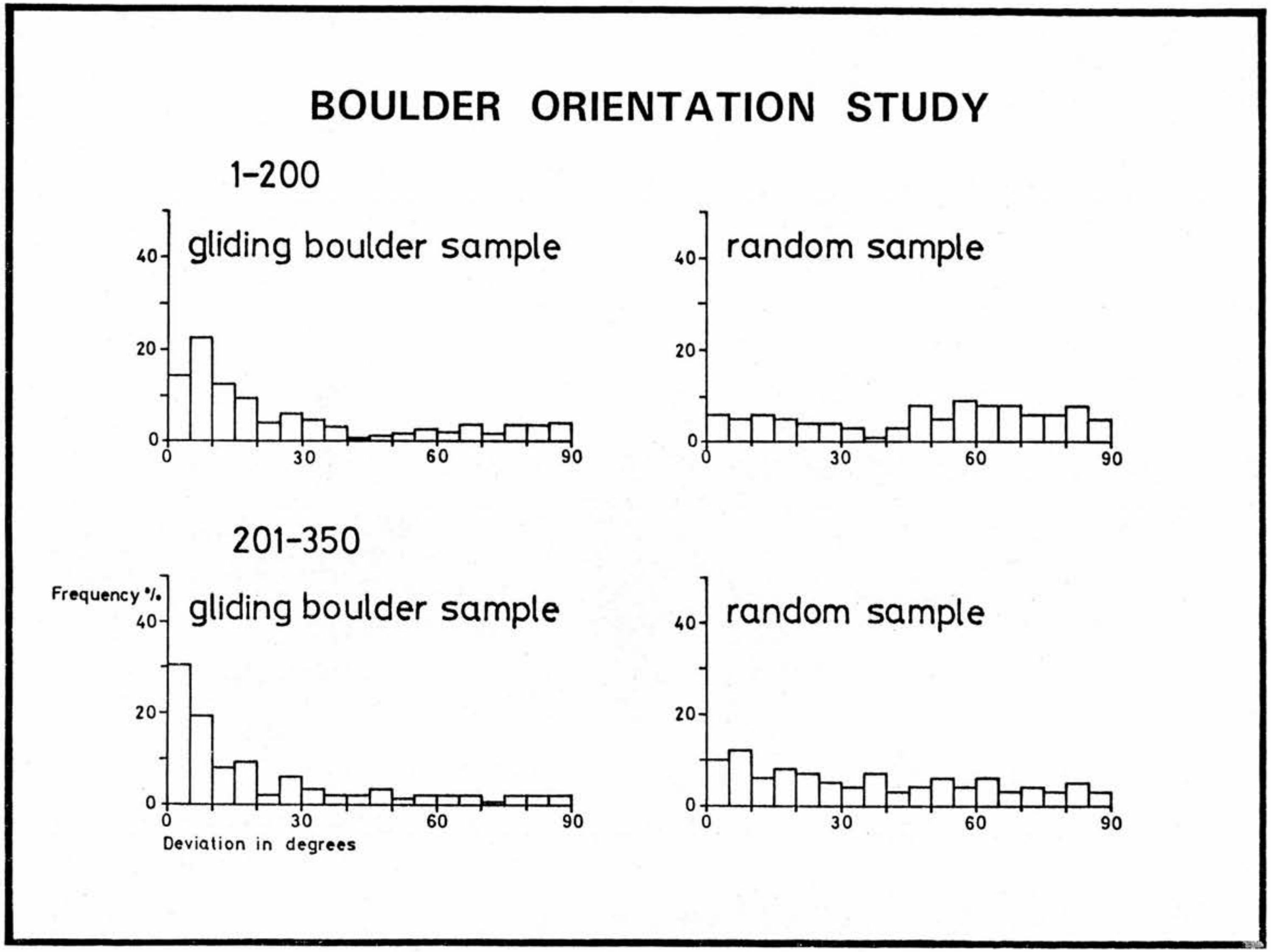
Orientation studies have revealed that gliding boulders can have their long axis oriented at any angle to the direction of maximum slope, from 0° to 90°. Gliding boulders from the metamorphic area occurred throughout this range, but the majority were found to be oriented more nearly downslope (Figure 7.8). The minimum number of observations occurred at around 45° to the slope direction with a slight increase in the frequency of occurrences towards a secondary peak at 90°. This feature is not shown by the granite sample (Figure 7.8), which shows a peak at 0°-5° followed by a rapid tailing off of occurrences, with very few examples deviating by more than 20°.

The metamorphic sample shows 69% within 30° of the downslope direction and 77% within 45°. The calculated mean deviation from the downslope direction is 27.6°. Samples from the granite area are similarly distributed. A little over 75% are oriented within 30°, and 82% within 45°. The mean angle of deviation is 21.4°.

The total sample showed that 71.7% occurred within 30° of the downslope direction and 79.4% within 45°, with a mean angle of deviation of 24.9°.

Tufnell (1972), in his study of 500 gliding boulders in northern England, found 83% of the examples oriented parallel to the direction of maximum slope, and 17% perpendicular to this direction. These results do not qualify the limits of the categories but it is assumed that each category lies within 45° of the downslope or cross-slope direction. These findings are very similar to the results of the present study, that is 79.4% compared to 83% oriented within 45° of the downslope direction.

In the case of irregular boulders which may be triangular or almost circular in plan, the stating of a long axis direction will give a misleading impression of the nature and relative dimensions of the edge they present downslope. Nevertheless it is evident that many gliding boulders have their longest



BOULDER ORIENTATION STUDY
1-200
gliding boulder sample
random sample
201-350
gliding boulder sample
random sample
Frequency %
0
20
40
0
30
60
90
Deviation in degrees

Figure 7.9

dimension across the slope or obliquely to their direction of travel. Such a relationship would appear to be restrictive to gliding, but it could be that many boulders are actually in the process of rotating, or have been deflected having met some obstruction in their path (Photograph 7.3).

It was considered to be possible that a downslope orientation could be characteristic of all boulders upon these slopes in these areas, even those that could not be seen to be gliding, especially if the slopes are or had been active gelifluction slopes. Such a possibility was tested by sampling 100 boulders from each of two quadrats, one situated upon an east-facing valley side of the Allt a' Gharbh-Choire in the metamorphic area (NO 163794), and the other upon a south-west-facing valley side of the Glas Allt valley of the granite area (NO 258845). Sampling was done at intervals of ten paces to build up a quadrat of 100 paces x 100 paces.

The results of the study are shown in Figure 7.9, from which it is apparent that the orientations are fairly evenly spread over the 0^{o} to 90^{o} range, suggesting that the boulders are not subject to any preferential aligning force. The samples had mean orientations of 48.8^{o} and 36.7^{o} respectively. Orientation results from the two quadrat samples were statistically compared (Kolmogorov-Smirnov) with the orientation results of their respective gliding boulder samples. Both pairs are different at the 99.9% confidence level. From this finding it is concluded that gliding boulders tend to be oriented with their long axis parallel to the direction of maximum slope, whereas similar boulders upon the same slope that do not show evidence of movement by gliding tend to be randomly oriented with respect to the slope direction. Thus, boulders that are of a nature or in a situation that causes them to glide become re-oriented towards a position of least resistance to forward motion, or, boulders that are initially deposited with their long axes down-slope are more likely to move by gliding. It can be seen that a downslope orientation is not the only prerequisite for gliding, as boulders with downslope orientations do occur that are not gliding, and gliding boulders occur that have their long axes oriented across the slope. The latter category of boulders must have some compensating attribute, such as the form of their base, the nature of their leading (long) edge, or they may be in a temporary dis-equilibrium after being deflected or rotated by an obstacle in their track (eg. Photograph 7.3).

Furthermore, it can be tentatively suggested that the non-gliding boulders, scattered over the same slopes as well developed gliding boulders, do not show any evidence of movement by their fabric pattern. Gelifluction deposits are generally regarded as having their contained stones oriented parallel to the direction of movement, and stones in other periglacial landforms usually show some preferred alignment of the fabric (Lundqvist, 1949). The orientation of isolated surface stones upon gelifluction deposits has received little attention, but it is to be expected that they would be influenced by similar forces to the stones buried in active gelifluction slopes. If this is the case then the general lack of any preferred orientation of these boulders indicates that the slopes in this area are relatively stable. A similar conclusion was drawn from the presence upon these slopes of well established mats of Vaccinium myrtillus (see the Slope Vegetation section).

The Bow-Wave: The bow-wave is the turf-roll and/or debris ridge pushed ahead of a gliding boulder during its downslope travel. Bow-waves are a further indication of movement, supplementing the furrow as evidence for the recognition of gliding boulders, but bow-waves are not ubiquitous. Gliding boulders may have a long, well developed furrow when the bow-wave is minimal or absent.

Detectable bow-waves were developed ahead of 129 of the 200 metamorphic gliding boulders, and in front of 66 of the granite gliding boulders. The height of each of these bow-waves was measured. Such a measure raised many problems in the field as the bow-waves invariably had an undulating crest, the ground in front of them was irregular, and tufted vegetation upon and around them made the selection of measurement points

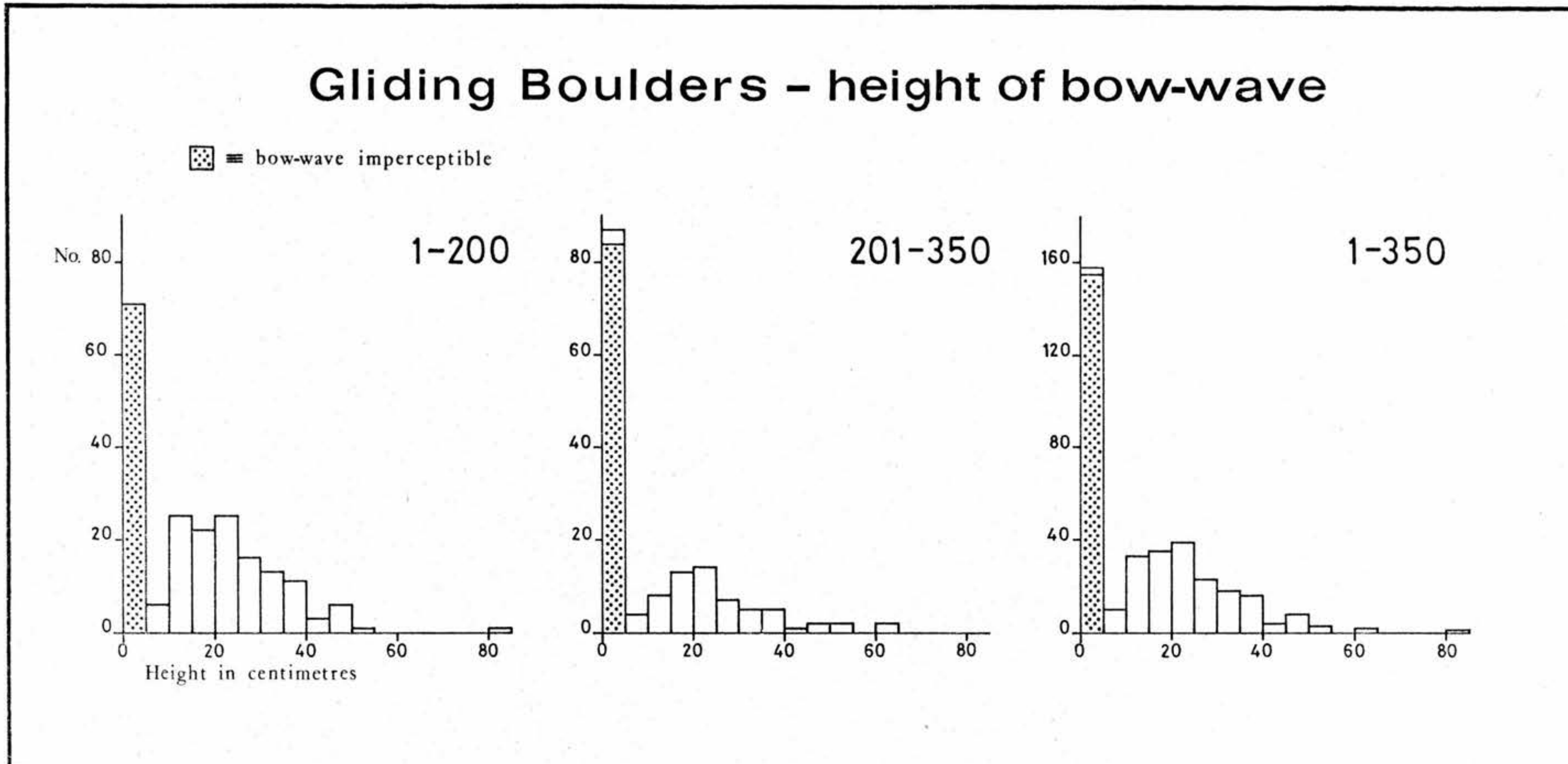

Gliding Boulders - height of bow-wave
≡ bow-wave imperceptible
1-200
201-350
1-350
No.
Height in centimetres
0
20
40
60
80
120
160

Figure 7.10

extremely difficult. Bow-wavelength, or thickness, was an even more difficult problem as the bow-wave usually graded into the slope ahead of the boulder. All of the 129 metamorphic gliding boulder bow-waves were measured for length and only 60 from the granite area (Figure 7.10).

Bow-waves ranged in height from 6 to 83 cm in the metamorphic area, and from 2 to 63 cm in the granite area. Lengths ranged from 4 to 89 cm, and from 2 to 86 cm respectively. Mean dimensions reflect the generally small nature of these features. They averaged 15.2 cm high by 16.7 cm long in the metamorphic area, and 10.5cm high by 12.4 cm long in the granite area. The smaller bow-waves in the granite area, probably reflect differences in the nature of the regolith and vegetation. Regolith in the granite area was coarser, more sandy and gravel-like and so would be more likely to be pushed aside and less likely to build steep ridges. The predominance of woody-plants with long deep root and rhizome systems tends to anchor the upper surface and so each plant would be stretched and torn off by the boulder, or overrun by it, rather than being pushed up ahead. The regolith in the metamorphic area is more silty in general, and so produces earth wrinkles more readily. Also the vegetation tended to be more dominated by grass species, hence these more superficially rooted plants are more likely to be pushed ahead as a turf-roll.

The idealised form of a bow-wave is of an unbroken roughly crescentic mound contacting the gliding boulder at its upslope edge and having a steeply sloping convex outer face. In practice few bow-waves were found to be complete, many being developed only at the front or at one side or the other of the boulder, or in any combination of frontal or lateral bow-waves. Some gliding boulders were observed to be cutting through their bow-wave. Photograph 7.5 illustrates this phenomenon. Gliding boulder 310 (Photograph 7.4) has a bow-wave on its left-hand side which contains a buried boulder around which the gliding boulder is being deflected. The bow-wave is covered by vaccinium, which is extending up onto the top surface of the boulder.

Gliding boulders are not infrequently seen to be following each other down the same furrow as a 'boulder train', a phenomenon observed by Lyford et al. (1963) in the Harvard Forest, Massachussets. The later boulder rarely produces a bow-wave. In many cases gliding boulders have collided with a stationary boulder or another gliding boulder, and so bow-waves are absent.

Several excellent examples of such furrow sharing and collisions were gathered. Granite gliding boulder number 205 had terminated against the projecting edges of five buried granite fragments after travelling for 56 cm down a 19^{o} slope. Granite boulder 206 was only 2 cm away from boulder 205 having travelled for 60 cm down an adjacent slope to meet boulder 205 obliquely. Granite boulder 227 had terminated against a collection of granite debris after travelling for 240 cm down a 21^{o} slope. A second boulder was proceeding down the same furrow only 97 cm behind. Granite boulder 233 also had reached a pile of partly buried fragments and was being followed by a second boulder down the same furrow.

Lateral bow-waves are commonly developed for short distances along the sides of many gliding boulders. A large lateral bow-wave may develop along one side of a boulder if it is rotating. Granite gliding boulder 275 had a particularly well developed right-lateral bow-wave.It had collided with two fixed boulders, and so had begun to pivot against these boulders, the leading edge pushing up a bow-wave. Granite boulders 306 and 307 had travelled 360 cm and 103 cm respectively down the same slope, the most recent portion of both furrows being side by side separated only by a levee-like ridge of material, forming what might be described as a common lateral bow-wave.

Bow-waves were thus seen to be highly variable and irregular features, which may or may not be present in front of a gliding boulder. They can develop as frontal, frontal plus double or single lateral, or single or double lateral only. In some instances bow-waves were absent, and replaced by a slope boulder or another gliding boulder.

Lithology: The range of rock types sampled was limited. All the rocks from the Lochnagar area were medium grained granite.

Many contained quartz veins and bands. In the metamorphic area the predominant rock types were schists of many compositions (71.5%), combined with some gneissic rocks. The remainder were quartzites (28.5%).

Factors other than the lithology of the boulder would appear to control the development of gliding boulders. Gliding boulders consisting of Carboniferous sandstone and limestone, Ordovician andesites, rhyolites and tuffs, granite and gneiss (Tufnell,1972, pp.245-246) have been recorded. It is necessary that the bedrock should weather to produce resistant boulders and not break down completely. Lithology will have some control upon the size of the boulder produced and its form when weathered. The nature of the underlying rock also has some influence upon the characteristics of the regolith, except of course in areas covered by foreign glacial deposits, and so upon the ability of the soil to provide conditions suitable to gliding boulder development.

Both the granite rocks and metamorphic rocks of the present study area appear to provide boulders and regolith conditions suitable to gliding boulder development.

PART 1: SUMMARY AND CONCLUSIONS

The Distribution of Gliding Boulders

Gliding boulders were found at altitudes between 450m to 1100m a.s.l. in the south-east Grampian study area. The altitudinal limits of the distribution reflected the range of altitude between the highest and lowest points investigated. Thus no true upper and lower limits to gliding boulder development were determined.

The study revealed that gliding boulders are present on slopes of all aspects and do not show a preference for slopes of any particular aspect. Two modal peaks within the distribution of the metamorphic sample have been shown, statistically, to be a result of the dominance of slopes of certain aspects (40° to 120° and 280° to 340°) within the sampling areas. Thus aspect does not appear to determine the occurrence of gliding boulders.

Gliding boulders occurred upon slopes between 9° and 38°

gradient, but were mainly concentrated upon slopes between 11° and 29° (95%). This concentration has been shown to be due to factors other than the range or proportion of available slopes within the sampling area. A randomly collected sample of slope angles within the sampling situations was shown to be statistically distinct (99.9% Kolmogorov-Smirnov) from gliding boulder sample slope population. It appears that gliding boulders develop preferentially upon slopes between the angles of 11° to 29°.

The vegetation of the slope did not appear to restrict the occurrence of gliding boulders, which were found upon slopes vegetated with grasses, <u>Vaccinium myrtillus</u>, and <u>Calluna vulgaris</u>, in various proportions and combinations. The presence of vaccinium upon these slopes suggests that the regolith is fairly stable at present .

The Characteristics of Gliding Boulders

The furrows behind gliding boulders ranged in total length from 13 cm to 888 cm. Furrows in the granite area were on average longer (mean 127.73 cm) than those in the metamorphic area (mean 71.93 cm). Many furrows had an upper section much constricted by vegetation, occurring above a large vegetation tuft within the furrow floor. Straight furrows were the norm, directed down the line of steepest slope. Very few winding, curved, or angled furrows were observed, and none that crossed the slope obliquely. Vegetation within the furrows was the same as that upon the slopes outside. The cross-sectional form of the furrow was usually rectangular or U-shaped or, more rarely V-shaped.

Boulders in the granite area were larger on average than those in the metamorphic area. Granite gliding boulders ranged from 39 to 240 cm long, 23 to 200 cm wide and 7 to 102 cm high, metamorphic gliding boulders from 38 to 215 cm long, 20 to 150 cm wide and from 9 to 69 cm high. The average boulders were 113.5 x 70.0 x 38.3 cm, and 82.5 x 51.7 x 28.3 cm respectively. The size differences are considered to be a result of the different lithologies of the two areas and reflect the different responses to weathering.

The shape of the upper, above ground portion of a boulder does not appear to prevent movement by gliding. Only 48% of the 350 boulders sampled had shapes broadly resembling a rectangular prism, the other 52% were classified as ellipsoidal, triangular, triangular prismatic, pyramidal and irregular.

Gliding boulders tend to be oriented with their long axes almost parallel to the slope direction. This measure does not take into account the form of the leading edge of the boulder, or the shape of its sliding surface. Almost 72% of the total sample (350 boulders) were oriented with their long axis within 30° of the downslope direction. A study of boulders scattered over the same slopes revealed that boulders without furrows, which are therefore regarded as being almost stationary, had their long axis oriented randomly with no preferred direction apparent.

Only 56% of the gliding boulders in the study area were pushing up identifiable bow-waves. Bow-waves were generally low, usually less than 30 cm high but occasionally reaching a height of up to 83 cm. Frontal and lateral bow-waves in various combinations, with either or both absent, were more common than the crescentic bow-waves usually described.

PART 2: THE MOVEMENT OF GLIDING BOULDERS

Factors Controlling Gliding Boulder Movement

The minimum distance that a gliding boulder has travelled can be determined by measuring the length of the furrow. It has been concluded that the gliding boulder slopes are not currently experiencing very active gelifluction, but evidence from the narrowing of furrows and the indistinct form of their upper sections suggests that imperceptible creep processes are operating. Thus the length of the furrow only indicates the relative movement of the boulder, the rate at which its furrow creation exceeds the rate of furrow obliteration processes.

In the absence of accurate information concerning the rate and mode of operation of soil creep processes in this area, and the lack of knowledge about the starting point of these boulders, the furrow length is the only evidence of the distance travelled by any particular boulder. Despite the limitations of this measure as an indication of the distance moved, attempts were made to correlate the furrow length with the other measured parameters to investigate the degree of control of each factor.

Simple linear regression was employed to investigate the relationship between the furrow length of the two gliding boulder samples and features of the terrain and of the boulders. If, for instance, the length of the furrow increased directly, or perhaps inversely, as the slope angle increased then this relationship would be revealed by a high determination ratio (R^2 approaching unity). Conversely a poor relationship, in which the distribution does not approximate to a linear relationship, is indicated by a low determination ratio (R^2 approaching zero).

The total furrow length, the dependent variable, was correlated with each of the terrain parameters and each of the relevant boulder parameters to test the degree of control of each factor.

The results of the regression analyses revealed low correlations in all cases, as shown below:

		metamorphic area	granite area
Total furrow length with			
	Altitude	0.131	0.019
	Aspect	0.020	0.036
	Slope Angle	0.163	0.013
Total furrow length with			
	Boulder Volume	0.002	0.074
	Boulder Surface Area	0.007	0.063
	Boulder Height	0.015	0.068
	Flatness (Surface Area/Height)	0.005	0.024

These results indicate that no single factor explains more than 16% of the observed variations of the total furrow length. Thus, in the granite area only 1.9% of the total variation in furrow length is associated with changes in the altitude of the site, 3.6% with changes in the aspect, and 1.3% with the slope angle. Slope angle in the metamorphic area appears to explain 16.3% of the observed variation of furrow length, altitude 13.1% and aspect 2.0%.

No single factor among those examined appears to exert a dominant influence upon the movement of gliding boulders. It is possible that simple relationships could never be established if the furrow length is not a true indication of the total movement. Nevertheless the technique of multiple regression analysis was attempted to investigate the possibility that several simple independent variables might explain the observed variation in the total furrow length.

The basic concept of multiple regression is to produce a linear combination of independent variables that will correlate as highly as possible with the dependent variable. Thus multiple regression allows an examination of the linear relationship between a set of independent variables and a dependent variable. It quite often happens that the simple regression method of predicting one variable by means of a related variable yields poor results, not because the relationship is far removed from the linear one assumed but because there is no single variable related closely enough to the dependent variable to yield good results. It may happen that there are several variables that, when taken jointly, will serve as a satisfactory explanation of the observed distribution.

	Metamorphic Sample	R^2
Total furrow length with	1. Slope Angle	0.163
and	2. Aspect	0.196
and	3. Boulder Height	0.204

	Granite Sample	R^2
Total furrow length with	1. Slope Angle	0.013
and	2. Aspect	0.038
and	3. Boulder Height	0.110

Thus, multiple regression does help to show that fuller explanations are achieved when several factors are taken into account. It can be seen that in the metamorphic sample 16.3% of the total variation in furrow length can be explained by changes in the slope angle, but 19.6% of the variation can be explained by the changes in slope angle combined with changes in the aspect of the site, and finally 20.4% by changes in slope angle, aspect and the height of the gliding boulder.

	Metamorphic Sample R^2	Granite Sample
Total furrow length with 1. Slope Angle	0.163	0.013
and 2. Altitude	0.244	0.030
and 3. Boulder Height	0.253	0.145
and 4. Boulder Volume	0.259	0.163

	Metamorphic Sample R^2	Granite Sample R^2
Total furrow length with 1. Slope Angle	0.163	0.013
and 2. Altitude	0.244	0.030
and 3. Aspect	0.247	0.084
and 4. Boulder Volume	0.247	0.198

No single variable explains more than 16% of the observed variations, and no combination of variables explains more than 26%. Within samples, different variables have different degrees of control, but the relative importance of each variable differs between the two samples. For instance, slope angle appears to exert the most control, among the terrain parameters, in the metamorphic sample, but aspect is the most important terrain parameter in the granite sample.

Among the boulder parameters, none of those selected correlates very highly with the total furrow length. The boulder volume was selected as this determines the relative mass to be moved; the boulder surface area indicates the amount of frictional surface; the ratio of surface area to height indicates the flatness of the boulder, thus giving the relative frictional surface or the relative area presented for frost heaving; and finally the boulder height was thought to be important in determining the likelihood of the boulder projecting above the surface of a snow cover allowing it to absorb radiation to promote basal melting and movement (C. Halstead, pers. comm.).

The shape of the boulder has not been considered in these investigations. As indicated in the discussion of the shape of gliding boulders, Tufnell (1972) believed that the optimum shape for gliding is a rectangular prism. An examination of the results reveals that from the metamorphic sample the average furrow length of gliding boulders classified as rectangular prisms is 72.2 cm as compared with an average of 71.6 cm behind non-rectangular prisms. The results from the granite sample are 116.4 cm and 135.1 cm respectively. The range of furrow lengths behind rectangular prisms in the metamorphic sample is 17 to 262 cm, compared with 15 to 317 behind non-rectangular prisms. Results for the granite sample are 13 to 410 cm compared with 23 to 888 cm respectively. Thus the rectangular prismatic boulders do not leave the longest furrows in either area. Also non-rectangular prismatic boulders leave the longest average furrows in the granite area, whereas the two categories leave, on average, almost the same length of furrow in the metamorphic area.

Summary and Conclusions

Attempts to explain the observed variations of furrow length behind metamorphic and granite gliding boulders in the South-East Grampian study area have shown that no single factor, among those recorded, can explain more than 16% of the observed variation. Consideration of the combined influence of up to 4 variables does not explain more than 25% of the observed variation in furrow length.

These results suggest that other factors are more important than those considered here, or that the total furrow lengths observed are not true indications of the total distance moved, over a similar period of time. Some boulders have apparently halted against submerged rocks and so the furrows can be expected to be too short for the time available, and it is possible that others have been obscured by vegetation development and/or soil creep processes and so are under-representative.

Many important factors have not been considered in this study. The particle-size distribution of the regolith and hence the moisture holding capacity and frost susceptibility can be expected to vary over short distances, affecting the rates of movement of adjacent boulders and even the same boulder as it moves downslope over varying materials. The slope angle results are generalised for this study: it is possible that boulders may have varying rates of travel as they progress down slope facets of the microtopography. Small-scale changes in the nature of the vegetation cover may also be important, offering varying degrees of resistance to travel, causing local variations in the dampness or insulation of the soil and hence influencing the effects of frost. Finally, and related to each of these factors, are the variations of the weather and how each site is affected, governed perhaps initially by aspect, but ultimately by the soil conditions, microtopography and vegetation cover which will influence the intensity and duration of frost cycles, gelifluction periods and snow lie conditions.

Many characteristics of the boulders thenselves have not been considered. The nature of the leading edge of the boulder, the shape of its sliding surface, and the depth of burial of the base all require examination.

THE PRESENT DAY MOVEMENT OF GLIDING BOULDERS

Marker Stake Experiments

There is very little agreement in the literature concerning the present day activity of gliding boulders. Tufnell (1972, p. 256) stated that "virtually no attempt has been made to determine accurately the rate at which ploughing blocks travel".

Only two studies describe the details of contempory gliding boulder movements in the British Isles. Johnson and Dunham (1963) concluded that gliding boulder movements on the Moor House Reserve in the Northern Pennines were usually slow, and rapid movements were seldom experienced. An exceptional shift of 1.5m in one year was recorded during their observation period. Tufnell (1972) measured the annual movements of five gliding boulders at varying altitudes on the Moor House Reserve. From the Moor House results, over the period 1965-1969, five main conclusions were drawn.

1. Gliding boulder movement was always slow, annual movements of 5.0 to 7.5 cm p.a. being measured.

2. Blocks that moved fastest in any one year were shown to do so in other years as well, and <u>vice versa</u>.

3. Accelerated rates of boulder movement occurred in some

years, and decreased rates in other years.

4. Fragment size was found to have a bearing upon the rate of displacement, smaller fragments travelling more rapidly than larger ones.

5. Rates of movement differed on slopes of approximately equal steepness.

The Present Study

In the summer of 1971 marker stakes were placed behind nine gliding boulders in the metamorphic area. Examples were selected from a range of slope aspects and slope angles.

Three examples were situated in the valley of the Allt a' Gharbh -choire (NO 165800), and six in the Allt Coire Fionn (NO 158788) to the north of Glas Maol.

During the summer of 1972 three gliding boulders upon the floor of the Stuic corrie of the Lochnagar Massif were included in the experiments. The three examples were situated by the shores of Loch nan Eun (NO 234854). The first season's experimental sites were checked for possible movements. All twelve boulders were re-examined in 1973 and again in 1975.

Site	Boulder	approx map ref.	Altitude	Aspect	Slope Angle	Furrow Length	Size	Axis Orientation
Metamorphic Area								
A	23	NO 178791	800 m	172°	24°	100	78/54/36	06°
B	46	NO 178799	880 m	308°	21°	48	118/61/28	06°
C	52	NO 179800	890 m	325°	28°	40	73/46/26	20°
D	73	NO 153788	660 m	348°	37°	93	47/32/25	18°
E	75	NO 154787	670 m	042°	28°	108	137/65/63	04°
F	76	NO 159783	700 m	060°	22°	140	127/80/23	02°
G	85	NO 159778	770 m	104°	21°	43	90/69/32	12°
H	87	NO 157788	680 m	214°	26°	35	60/54/39	20°
I	90	NO 159787	700 m	230°	23°	45	122/62/34	08°
Lochnagar								
J	253	NO 230856	910 m	320°	16°	217	140/117/102	04°
K	278	NO 231855	900 m	104°	14°	161	155/106/52	06°
L	291	NO 231853	920 m	328°	18°	106	130/61/50	00°

Method

The measurement technique closely followed that used by Tufnell

(1972, and pers. comm.).

Three wooden stakes, each of 2 cm diameter softwood dowel rod, were driven into the ground behind the boulder in a line ranging from approximately 12 to 37 cm from, and roughly parallel to, the upslope edge of the boulder. Tufnell found that his shorter, 30 cm long, stakes were occasionally displaced by frost heave and/or soil creep, but the larger 90 cm stakes showed no detectable movements. In the present study 30 cm and 45 cm stakes were used. Although 90 cm stakes had been produced, it was never possible to insert one into the ground for more than half its length because of the stony regolith and in some cases the presence of large boulders or bedrock at shallow depths. The 45 cm stakes were used wherever possible, but in many cases the shorter ones had to be used. Attempts were made to place the line of stakes at about 15 to 20 cm behind the boulder, but in practice the stakes had to be placed wherever they would penetrate.

The use of three reference stakes at each site allowed any shifts of an individual stake, relative to the other two, to be detected, and also enabled any turning motion of the boulder to be observed.

A steel panel pin was hammered in to the top of each stake to act as a measurement point. Three small crosses were cut into the upslope face of each boulder opposite their respective stakes. Two fine grooves, intersecting at approximately 90° were cut using a light hammer and a cold chisel. The grooves of the crosses were overpainted in aluminium paint to facilitate later identification.

Three sets of measurements were recorded at each site. Firstly, the distance between each nail and the centre of its respective cross was measured, and also the diagonal distances between the nails and the crosses. Secondly, the height of each stake above the ground was recorded in order to detect any changes in the stakes. Thirdly, the distance between the centre of each cross and the ground was measured so that any vertical movements of the boulders could be determined. The last two sets of measurements were subject to errors resulting from the uneven nature of the ground and the presence of tufty vegetation. The distances between the nails and the crosses were standardised at around

20 cm in order to minimise the field measurement errors inherent in using a rule over long distances.

Limitations of the Technique

There are several sources of error inherent in the measurement technique used in this study. Thus the results of the displacement measurements can only be regarded as indications of the order of magnitude of contemporary gliding boulder movement and cannot be accepted as absolute values of downslope displacement.

No information is available from the Scottish hills to indicate the depth to which stakes in the ground are likely to be affected by frost action and/or creep of the regolith. Results from the northern Pennines (Tufnell, 1972) showed that stakes up to 30 cm long may occasionally be affected by frost heave and/or downslope movement. Studies of hillslope creep in the southern Pennines (Young, 1960) indicated that only the upper 10 cm of the soil were affected by downslope movements. Freezing of the ground below a depth of 10 cm is rare in the Mesters Vig district of north-east Greenland (Washburn, 1969, p.94) an area that experiences a polar climate. In contrast Ragg and Bibby (1966, p.13) observed ice-lenses 50 cm below the surface on the summit of Broad Law, in the Southern Uplands of Scotland, in April. Halstead (1974, p.263) also working in the Southern Uplands, recorded near freezing temperatures at 30 cm depth, but extrapolated the freezing level even deeper. Hence it is possible that the 30 cm and 45 cm long stakes used in the south-east Grampian study have their bases secured at a depth rarely affected by movements of the regolith, but not necessarily to depths unaffected by winter freezing. Also, as already indicated, it appears that the ground surface is not subject to large movements because *Vaccinium myrtillus* is able to grow and survive in this area.

There was no evidence of any tilting or upthrusting of the stakes when the experimental sites were checked, although minimal movements of a few millimetres would not have been apparent. Longer stakes would probably be more reliable, but these would have to be made of iron.

It is difficult to assess the order of magnitude of the potential error accumulating from the measuring procedure. The exact location of the corner of the steel rule at the intersection of the cross cut on the boulder, could possibly vary the reading by 0.5 to 1.0 mm. The intersection was finely prepared, but small irregularities of the surface would inevitably occur, which could be expected to cause possible slight variations in the readings obtained. It should be stressed that no observable weathering of the boulder surface, in the grooves of the crosses, had occurred during the four years. This could be ascertained because each cross had been overpainted with aluminium paint and no detectable disruption of the paint films had occurred, only a slight dulling from silver to grey due to oxidation. Hence it seems certain that no part of the annual increments was attributable to a recession of the upslope face of a boulder by weathering.

The final possible source of error concerns the true positioning of the rule over the head of the panel pin secured in the top of each stake. Discrepancies may occur due to small variations in positioning of the rule or to parallax. The error is not expected to be above 0.5 mm at the most.

The preceding discussion suggests that the maximum error is likely to be only 1.0 to 1.5 mm. No estimate of any errors due to movement of the stakes can be calculated, but such movements are considered to be minimal, the stakes apparently penetrating to depths below which regolith creep generally occurs. At every site the measurements were repeated as a check upon the method. The results were found to be reproducible to within $\pm$ 1 mm in almost every case, and $\pm$ 1.5 mm in a few extreme cases.

Results

The results of each annual survey are shown below:

Boulder	1971-72 cm	1972-73 cm	1973-75 cm	Total cm	Average cm
A	0.00	0.05	0.15	0.20	0.05
B	0.07	-0.12	0.15	0.10	0.03
C	0.77	0.83	0.80	2.40	0.60
D	2.05	0.60	0.82	3.47	0.87
E	0.70	0.57	1.10	2.37	0.59
F	0.13	0.32	0.95	1.40	0.35

G	0.13	0.23	0.63	0.99	0.25
H	0.10	0.17	0.10	0.37	0.09
I	0.18	0.15	0.13	0.46	0.12
J	-	-0.03	0.17	0.14	0.05
K	-	0.12	0.17	0.29	0.10
L	-	0.12	0.62	0.74	0.25

The annual displacement of each boulder was regarded as the average of the three differences between each stake and its respective cross as measured in successive years. At most sites the variation between the magnitude of the three measurements was only about 1 or 2 mm, approximately the limits of error of the technique; hence the average serves to distribute any error or variation.

In only five instances was there any indication of a boulder turning as it moved, suggested by a consistently increasing difference across the three measurements. These were Boulder C 1971-72, Boulder D 1972-73, Boulder E 1973-75, Boulder G 1972-73, and Boulder I 1971-72. In all cases, except Boulder G they were turning anti-clockwise, or to the left as they moved downslope. No boulder appeared to be rotating over more than one year.

In only two instances were negative overall movements recorded. Both cases were for one year only, and were recorded at the slowest moving gliding boulder from the metamorphic area, and the slowest from the granite area respectively (Boulder B 1973-73, - 0.12 cm, and Boulder J 1972-73, - 0.03 cm). Other than at these two examples no individual stake to cross measurement was recorded as being negative.

All 12 gliding boulders showed some degree of postive down-slope movement over the total survey periods. Of the 9 examples from the metamorphic area over the period 1971-1975 the overall displacement ranged from a total of 0.10 cm (Boulder B) to 3.47 cm (Boulder D). The total in the granite area over the period 1972-1975 ranged from 0.14 cm (Boulder J) to 0.74 cm (Boulder L).

The largest annual displacement recorded was 2.05 cm (Boulder D 1971-72) and the smallest, disregarding the negative results, was 0.000 cm (boulder A 1971-72).

Discussion of the Results

Each of the 12 gliding boulders surveyed showed an overall positive downslope displacement over the respective study periods. With the exception of metamorphic boulders A and B and granite boulder J, whose overall total is 0.2 cm or less (which falls within the range of error of the technique), all the boulders showed definite downslope movements. The magnitude of the movements varied from year to year and between different boulders. Very little consistency occurs between the annual displacements.

Boulder D, the smallest boulder on the steepest slope (37^{o}) showed the largest overall displacement (3.47 cm), but in only one year did it have the largest annual displacement (2.05 cm in 1971-72). Boulder C, the second smallest boulder on the second steepest slope (28^{o}) had the second largest overall displacement (2.40 cm) and the largest annual displacement in 1972-73. Boulder E, on a 28^{o} slope, had the next largest overall displacement (2.37 cm), but it was the largest boulder surveyed, with a volume 15 times greater than boulder D. The fourth largest overall displacement (1.40 cm) was attained by boulder F, which was the third smallest boulder upon the sixth steepest slope angle (22^{o}).

There is no simple relationship observable between the boulder volume, slope angle and the annual distance moved. Nor does the aspect of the slope, or the orientation of the boulder appear to influence the annual movement rate. Many more complex variables are likely to be operative than the few simple ones considered here.

The results can be summarised in the form presented by Tufnell (1972), as follows:

1. Gliding boulder movement in the south-east Grampian study area is nearly always slow. The maximum measured for one year was 2.05 cm. Tufnell measured an annual maximum of 7 cm.

2. The results of the present study do not support Tufnell's (1972, p.258) conclusion that boulders that move fastest in any one year tend to do so in other years as well and <u>vice versa</u>.

It is possible to identify 'fast' and 'slow' boulders, but no boulder is faster than all the others in all years, and no boulder is slower than all others in all years.

3. Individual boulders exhibited accelerated rates of movement in some years and decreased rates in other years but there was no evidence of 'slow years' and 'fast years' as identified by Tufnell (1972). The total distance moved by all the boulders was greater in 1971-72 (4.13 cm) than in 1972-73 (2.80 cm), but many individuals moved farther in the latter period than during the former.

4. Fragment size does not have a direct bearing upon the rate of displacement. Tufnell observed that smaller boulders moved faster than their larger counterparts. In the present study the two faster metamorphic boulders were the two smallest, but the third most rapid was the largest metamorphic boulder (with a volume 15 times greater than the fastest boulder).

5. Rates of movement were found to vary on slopes of approximately equal steepness. The largest annual movements were not always on the steepest slopes.

Past Rates of Gliding Boulder Movement

Introduction

Contemporary movements of certain gliding boulders in the study area have been demonstrated and measured using marker stakes. These results, over such a short period, allow only tentative extrapolations to be made concerning the rates of movement of these and other gliding boulders in the area in the years preceding these experiments. In order to estimate rates of gliding boulder movement in the recent past, and to estimate the length of time required to produce the observed furrows, a method for dating the furrows at selected intervals was sought. As all the furrows were vegetated to some degree, the growth habits of the main plant species present were investigated.

Woody moorland plants such as heather (Calluna vulgaris) and the blaeberry (Vaccinium myrtillus) produce annual rings and thus provide a technique for establishing the minimum age of the surface upon which each plant grows, provided that the characteristics of the plants are understood. The principles can best be understood by examining the bases of dendrochronology, and investigating the nature of calluna and vaccinium growth.

Dendrochronology

The passage of time can be reliably measured by counting a sequence that is the result of the annual recurrence of natural rhythmic processes, such as the formation of the rings (West, 1968b, p.164).

Annual rings develop as a consequence of seasonal changes in the wood growth of trees and shrubs, and are formed inside the bark by the division of cambial cells. Spring growth is characterised by wood cells with large lumens, large thin walled wood or xylem cells. Summer and autumn cells are smaller, thick walled cells or latewood. A year's growth begins with large cells and ends with smaller cells, both types together comprising an annual ring. This phenomenon is also apparent in the stems of heather and vaccinium plants. An abrupt change between the last formed wood of one year and the first wood of the next year usually delineates the boundary between the growth increments (Fritts, 1966). The number of rings increases towards the base, so basal stem sections provide the longest and oldest ring width chronology.
The study of tree rings for the purpose of dating is known as dendrochronology, a science that is becoming increasingly sophisticated and extending its scope and methods (eg. Fritts, 1963, 1965, 1966; Stokes and Smiley, 1968). A very important application of dendrochronology is the possibility of obtaining a minimum age for a surface by determining the age of the oldest tree growing upon that surface. Within a particular climatic province dendrochronology is a very accurate method of dating (West, 1968b).

Studies of the growth rings of woody dwarf plants provide similarly accurate information but such a possibility has been largely neglected (Beschel and Webb, 1963), especially in geomorphological studies. Tree ring chronologies have been used to date snow avalanche tracks (eg. Potter, 1969), to determine rates of slope degradation (eg. La Marche, 1968), to find the minimum age of moraines (eg. Bechel and Webb, 1963) and to date glaciated surfaces (eg. Vieneck, 1967). Beschel and Webb (1963) used information from the growth rings of dwarf willows in their geomorphological study, but otherwise age information from woody dwarf plants is primarily used in botanical studies concerned with the sociology of heath communities (eg. Watt, 1955a; Ward, 1971; Tyler et al., 1973), vegetation productivity (eg. Chapman, 1967; Summers, 1972) and heather burning (eg. Kayll, 1966; Miller et al., 1966, 1969).

Ring counting from dwarf woody plants is thus a well established technique in biological studies, and it is from these that most of the knowledge has accumulated. The authors point to various precautions that should be observed during sampling and analysis, and also to the limitations of the techniques. The present study was concerned with heather and blaeberry, whose characteristics are described below.

Characteristics of the Growth and Distribution of Heather and Blaeberry.

Heather

Heather (Calluna vulgaris L.Hull) is a semi-sedentary dwarf shrub that may behave as a creeping dwarf shrub, often rooting adventitiously (Gimmingham, 1960). This process involves the dropping of rootlets from the prostrate, divergent stems that issue from the main plant. Heather is normally associated with more or less freely drained acid soils, mor humus and peat. It is characteristic as a dominant of west European heath communities. In podsol soils 80% of the root system of calluna is concentrated in the upper 13 cm or so of the soil, but with older calluna there may be a secondary zone of rooting just above a pan (25-30 cm). Calluna roots are generally confined to depths not exceeding 10 cm, a few sometimes reaching 18 cm.

The production of adventitious roots from stem bases is most vigorous when these are surrounded by moist moss or lichens, or by moist litter and humus. Gliding boulder furrows were often observed to be damp and carpeted by thick mats of mosses, hence furrows could be expected to provide conditions favourable to the formation of adventitious roots. It has also been shown (Gimmingham, 1960) that when decumbent branches lie on moist ground, particularly under the pressure of winter snow they root adventitiously at intervals. The accumulation and retention of snow in furrows would be expected to promote adventitious rooting both by the effect of its mass upon calluna branches, and by producing moist conditions.

Characteristically heather is widely tolerant in respect of temperature range and length of the growing season. It is also tolerant of severe exposure upon the mountains of Great Britain. It will survive on acid soils with a pH range of 3.2 to 7.0, but is normally found growing on soils of pH 3.5 to 6.5. Heather plants grow at elevations ranging from sea level to about 1050m. Watt and Jones (1948) found a solitary heather plant at 1095m on Beinn a' Bhuird in the Cairngorms. Calluna is highly susceptible to summer drought, but is resistant to frosts.

Calluna constitutes a substantial part of the diet of hill sheep throughout the year, particularly in winter. In summer preference is shown for the tips of growing shoots, whereas in winter larger portions including woody shoots up to 5 cm long are taken. Young calluna, up to 6 years of age, is extensively grazed in summer, but is largely avoided in winter. Older but vigorous plants are grazed throughout the year and thus provide the bulk of the food consumed in winter. From September to May 80% of the food of the red grouse (Lagopus lagopus Lath.) consists of calluna. This rises to almost 100% in March and April. Flowers and seeds are taken in the late summer and autumn. The feeding habits of the red deer (Cervus elaphus L.) have been studied in most detail on Rhum (Nature Conservancy, 1967) where it was shown that heather was lightly grazed by deer in summer, but heavily grazed in winter.

Hill sheep and red deer are fairly abundant in the metamorphic area. Red grouse and red deer are abundant in the Lochnagar area where only a few sheep are present. Some damage of heather stems by grazing is to be anticipated and even complete removal of branches is possible. Heather is burnt for sheep and grouse, but no burning occurs in the areas sampled, so damage to, or absence of branches due to this agency can be ruled out.

Blaeberry

Blaeberry (*Vaccinium myrtillus* L.) is a deciduous dwarf shrub with an extensive rhizome system. The aerial shoots are usually between 10-60 cm in height. Its erect branches bear dark blue/black berries 3 mm in diameter (Butcher, 1961). Like calluna, blaeberry is a calcifuge species (Tutin *et al.*, 1972). It is found native on non-basic soils of woodlands, heaths and bogs throughout the British Isles, and is very common on the moors and woodlands of Highland Scotland at all levels from sea level to 1300m (Ritchie, 1956). Blaeberry is more tolerant of exposure and shade than calluna and becomes dominant in a zone higher on the mountains, ascending to over 1200m (Clapham *et al.*, 1962). Calluna may repress the growth of blaeberry in part at levels between 600-850m (Ritchie, 1956). Blaeberry is susceptible to damage by frost, thus the altitudinal zonation depends in some degree on the degree of snow protection.

The form and extent of the blaeberry stand are determined by the growth of the rhizome (the rootstock, the underground stem that produces roots and leafy shoots). The older rhizome is often contorted and is abundantly branched in its middle parts. In soils with a mor layer the older rhizome usually lies at the boundary with the mineral soil, the younger rhizome being more superficial. Old roots at the proximal end of the rhizome may descend more than 45 cm into the mineral soil. Roots on younger rhizomes are usually very fine and are concentrated in the upper part of the humus. A rhizome unit is commonly 2 metres or more in length, has many branches bearing aerial shoots of various ages on their distal parts, and is decayed at the proximal end.

Moor burning is the most widespread biotic factor that affects blaeberry (Ritchie, 1956). Burning usually destroys only the aerial shoots, and the surviving rhizomes are able to initiate rapid colonization. Regular burning of the areas from which samples were taken did not occur.

Sheep will graze blaeberry. This stimulates further growth in the form of branching to produce a dense bushy habit.

Age Determination: Limitations and Sources of Error

Watt (1955a) pointed out some of the limitations to the use of heather ring counting. The only growth phases of heather that are capable of precise estimation are the building and mature phases. The pioneer phase of heather lasts anything up to 3 to 6 years after seeding, the building phase up to 15 to 20 years old, and the mature phase up to about 25 years old (Gimmingham, 1960). Heather enters the degenerate phase after about 25 years.~~old~~.

Even by the method of ring counting there is some uncertainty as rings are not always complete,the limits of individual rings are not always clear, and seedlings of a known age have occasionally shown fewer rings than the actual age (Watt, 1955a, p.497).

It is important that the base of the main stem is sampled. The stems growing from adventitious roots will be younger than the main stem.

Blaeberry is a long lived shrub. The aerial shoot may attain an age of 20-30 years.~~old~~. Ritchie (1955) gave ages of 25-30 years for examples from moorland near Sheffield.

For ring counts of blaeberry stems, sectioning of the stem base is necessary. Some clearly identifiable character is required to define the stem base. Flower-Ellis (1971) located the point at which there is a transition from ridged to smooth bark.

Since rings are usually irregular and may be incomplete several radii need to be examined, preferably at least two sections from each stem. In old stems that show an eccentric ring development it is advisable to check the ring count on the two or three greatest radii.

There are two main sources of error (Flower-Ellis, 1971). Firstly, the ring width has a tendency to decrease down the axis, and not in a regular manner. Consequently basal rings are often so narrow (less than <u>ca</u>. 0.005 mm) that the ring may not be counted. Secondly, the current year's ring may not be fully formed at the time of sampling, and may not be counted.

Greater error is to be expected as the age of the bush increases. Up to 15 years of age the ring count can be expected to underestimate the actual age by one year at the most. In bushes older than 15 years, the underestimate is likely to be at least 2 years.

Method

Samples of the basal stems of common heather (Calluna vulgaris) and blaeberry (Vaccinium myrtillus) were collected from the furrows behind four gliding boulders. A linear sampling technique was used. Extensive examination of many gliding boulder furrows yielded only four furrows that contained more than three or four large heather or blaeberry plants with their master roots in the furrows. As the technique of using dated stems to estimate the rates of gliding boulder movement was only experimental, many stems from each furrow were necessary in order to assess the value of the method. Hence only a few examples were able to yield sufficient stems to be of value in this preliminary investigation.

The central basal stems of all specimens of heather and blaeberry plants rooted in each furrow were cut close to the ground. Samples approximately 10 cm long were retained, and the basal ends were clearly marked. Each stem was labelled and its distance from the upslope edge of the gliding boulder recorded.

In the laboratory annual ring counts were carried out using two methods. Thin sections were prepared from each stem following the procedure described by Wallis (1966, p.p.12-22). This involved soaking short lengths of each stem overnight in water to soften the wood and prevent splitting when cutting. A section-cutting razor was then used to produce thin transverse sections from the prepared stems. Temporary slides were made, mounting the sections upon fine glass slides using glycerine. Cover plates were found to be unecessary, especially as the recognition and distinction of individual rings was facilitated in certain stems by staining whilst the mount was under the microscope. Several sections from each stem were mounted, and some required examination both stained and unstained when the rings were indefinite. Counting was carried out under a monocular microscope of 60-100 times magnification.

In some cases it was possible to perform ring counts using the prepared butt end of stems. A flat surface was created using a section-cutting razor. The surface was examined under a binocular microscope of 10 times or 20 times magnification, using surface reflected light. Staining the heather stems with safranin was occasionally found to be necessary. In the case of blaeberry stem sections a physical staining process using ink (permanent black Quink) was employed. This method reveals a contrast at the boundary of two rings as the stain is retained in the vessels. Ring boundaries are shown as a thin, black line.

The age information from the ring counts was plotted graphically upon time and distance diagrams. The age of each stem was plotted at its appropriate distance from the upslope edge of the boulder. Graph A was constructed from age counts upon 5 vaccinium stems, Graph B from 16 vaccinium stems, Graph C from 8 vaccinium stems and 1 calluna stem, and Graph D from 2 vaccinium stems and 4 calluna stems.

Sampling Areas

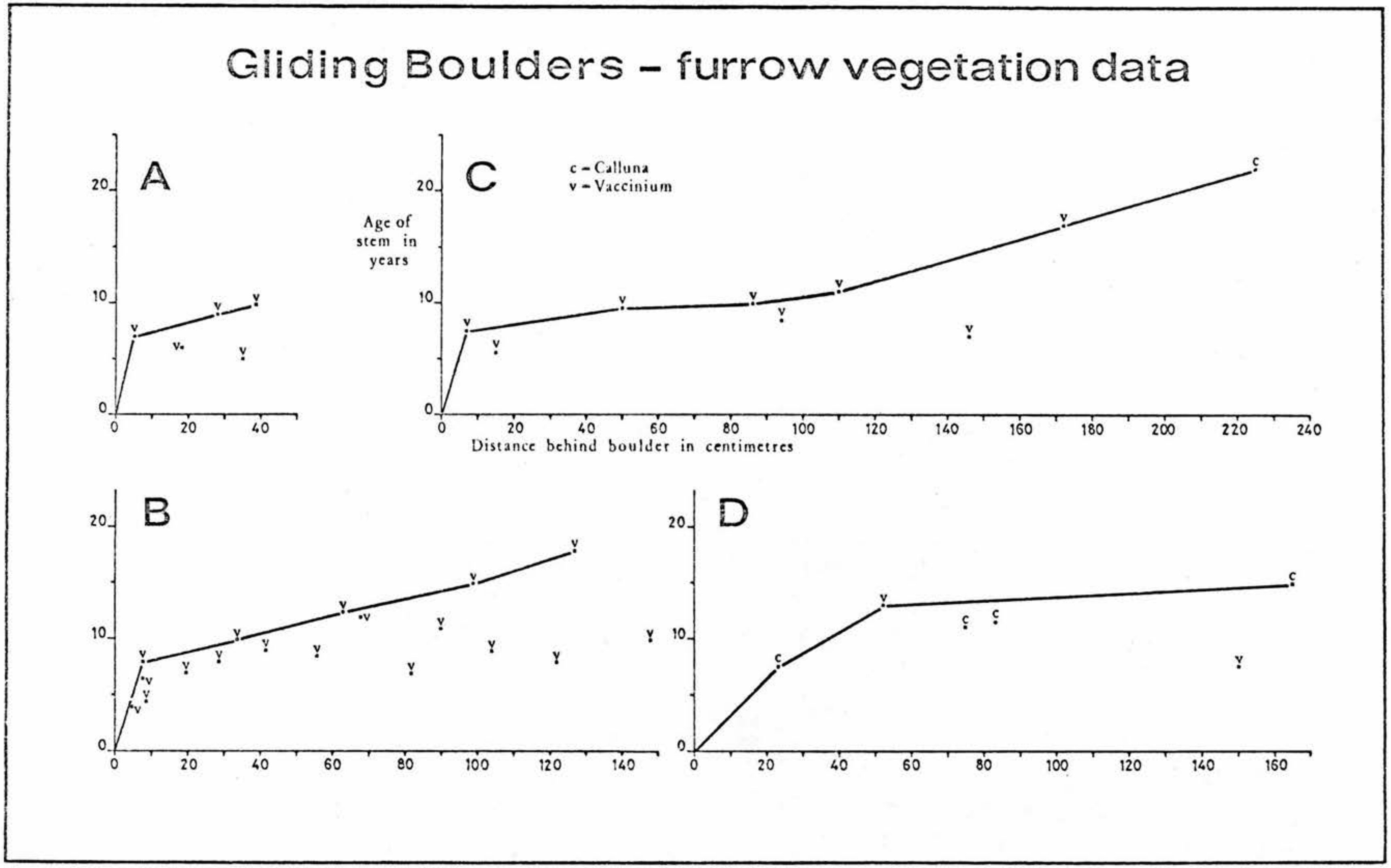
Boulders A and B are examples of metamorphic gliding boulders from the valley of the Allt a' Gharbh-choire (NO 165800), and boulders C and D from the granite area, in the valley of the Glas Allt burn of Lochnagar (NO 260840).

Boulder	approx map ref	approx altitude	aspect	Slope Angle	Furrow Length in cm	Boulder Size in cm	Deviation of long axis
A	NO 177798	840 m	246°	20°	44	25:46:26	82°
B	NO 176792	870 m	238°	28°	171	79:59:26	02°
C	NO 248850	1020 m	184°	16°	254	116:82:20	04°
D	NO 257844	780 m	212°	15°	166	143:113:48	10°

Results

Graphs A, B, C and D show the results of the studies in each of the four furrows (Figure 7.11). The vertical line upon each graph represents the upslope limit of each furrow.

The graphs were constructed on the premise that the furrow floor upslope of a particular dated plant could not be younger



Gliding Boulders – furrow vegetation data
A
B
C
D
c – Calluna
v – Vaccinium
Age of stem in years
Distance behind boulder in centimetres

Figure 7.11

than that plant; therefore only plants older than the oldest stem occurring on the downslope side of it were included when drawing the curve. Regression analysis was not used in this study because it is to be expected that younger plants will be arriving at any point along the furrow at any point in time. The diagnostic plants are the oldest ones.

Upon this basis the four graphs (Figure 7.11) show the maximum rate of travel of four gliding boulders over the last 10 to 22 years, and over 39-225 cm of travel. It appears that each one of the four boulders has undergone a rapid deceleration in recent years, from a rate of about 10 cm to 20 cm per year between about 8 to 18 years ago, with 56 cm per year or more in some extreme cases (Graphs C and D), to about 0.7 cm to 3.1 cm per year over the last 7 or 8 years.

Discussion of the Results

The apparently rapid rate of travel of these gliding boulders before about 7 years ago could possibly reflect a true overall slowing down of these features to rates similar to those measured by the stake experiments, or alternatively it is suggested that the upper sections of the furrows do not contain plants of a truly representative age.

It has been shown, in the introduction to this section, that heather can reach an age of more than 25 years, at which age it is only entering the fourth stage of its life cycle, and vaccinium plants up to 30 years old have been recorded (Ritchie, 1955). Thus older plants than those present could be expected. There was a scarcity of stems of more than 15 years old, the maximum age being 22 years (Furrow C). The possibility of recent heather burning in these sample areas has already been rejected, but no historical data is available to indicate that heather burning, or even chance moor fires could not have destroyed the vegetation of these areas about 20 years or so ago. Another possibility is that greater numbers of deer, or sheep, could have grazed the area more heavily about 20 years ago. In the absence of such information the results can only be intepreted as they appear, bearing in mind the possibility that the upper sections of the furrows are probably dated 'too young'. All of the dated points are minimum ages; that is, time must be allowed for the plants to colonise the areas vacated by the boulder.

Thus all the dates present will be too young by a few years.

The average annual rate of progress between each data point can be calculated to give an impression of the rate of movement of each boulder over different periods. These rates are summarised below.

Boulder A		Boulder B		Boulder C		Boulder D	
years ago	average rate p.a. cm						
9-10	11.0	15-18	9.3	17-22	10.6	13-15	56.5
7-9	11.5	12.5-15	14.4	11-17	10.3	7.5-13	5.3
0.7	0.7	10-12.5	11.6	10-11	24.0	0-7.5	3.1
		8-10	13.0	9.5-10	72.0		
		0-8	1.0	7.5-9.5	21.5		
				0 -7.5	0.9		

The overall average rates of movement of each boulder are

Boulder A	3.90 cm p.a.	over 10 years
Boulder B	7.05 cm p.a.	over 18 years
Boulder C	10.23 cm p.a.	over 22 years
Boulder D	11.00 cm p.a.	over 15 years

If the relative ages of the upper sections of the furrows are truly represented by the stem dates obtained then all the boulders have shown a marked decrease in their annual rate of movement over the last 7 or 8 years. The average rate of travel over the last 7 or 8 years varies from 0.7 to 3.1 cm p.a.. With the exception of boulder D, the average rates are not dissimilar to those calculated from the marker stake experiments, in which average movements ranged from 0.03 cm p.a. to 0.87 cm p.a. over the four years.

Average annual rates, calculated from the plant stem data, for the periods before the last 8 years are invariably greater, generally ranging between 5.3 cm p.a. to 24.0 cm p.a. with 56.5 cm p.a.and 72 cm p.a. indicated in two extreme cases

(Boulders D and C respectively). The lower of these rates is more similar to the maximum rate of 7.o cm p.a. recorded from the northern Pennines (Tufnell, 1972), but even the extreme rate is only 50% of the exceptional movement of 150 cm in one year recorded by Johnson and Dunham (1963) in the northern Pennines. Thus it is not unlikely that the faster rates indicated upon the graph are realistic and so the graphs might truly reflect a slowing down of these boulders over the last 7 or 8 years.

Such a decreased rate of movement could be due to a number of factors. As none of the boulders had recognisable bow waves it does not seem likely that they are being restrained by pushing a larger bow wave ahead of themselves. In no case was a boulder entering a slope section that had a lessening angle, different kind of vegetation to that which it had travelled through, or, as far as could be senn from a superficial examination, a regolith of different characteristics. The deceleration probably represents a lessening of the severity of winter climates in recent years, or a change in their characteristics with less snow fall or shorter snow lie. The lack of screen and ground temperatures for these immediate areas makes such a speculation very tentative.

PART 2: SUMMARY AND CONCLUSIONS

Marker stake experiments in the study area have shown that certain gliding boulders are moving downslope at between 0.05 cm to 2.05 cm a year, with average annual rates of 0.03 cm to 0.87 cm a year over the last four years.

A technique for dating the minimum age of the furrow at points along its length, by counting the growth rings of Calluna vulgaris and Vaccinium myrtillus plants rooted in the furrow, has shown that movement rates of this order have probably characterised the last 7 or 8 years. Prior to this a more rapid rate of annual movement, of the order of 5.3 cm to 24.0 cm a year or more in some cases, is suggested by the plant dating evidence.

Neither of these techniques revealed any simple relationship between the annual rate of travel and any of the terrain or boulder parameters. A similar conclusion was drawn from the analysis of the 200 metamorphic gliding boulder results, and the 150 granite gliding boulder results. No measured terrain parameter was able to account for more than 16% of the observed variations of the total furrow length, and no boulder parameter more than 7.4%. Attempts to correlate several of the measured parameters with the total furrow lengths yielded similar results. The use of four different parameters in stepwise multiple regression could only account for up to 26% of the observed variation in total furrow length.

From these results it is concluded that, although gliding boulders are active at the present day, the rate of travel varies from year to year and there appear to have been periods of accelerated movement from about 8 to 20 years ago. The annual or periodic variations in the rate of travel cannot be simply explained by the range of variables measured in the present study.

CHAPTER 8

ROCKFALLS, SCREES AND AVALANCHES

Introduction

Many different transport processes affect mountain slopes. Two groups are primarily distinguished (Chapter 4): rapid, momentary processes on the one hand, and slow, continuous or long lasting processes on the other. Slow processes of congelifluction and creep have been considered in the earlier chapters on lobes (Chapter 5), terraces (Chapter 6), and gliding boulders (Chapter 7).

The momentary processes, such as rockfalls, mudflows, avalanches, and landslides, are difficult to record because of their sporadic occurrence, but nevertheless have significant geomorphological consequences. Among the rapid transport processes working on and modifying the steep slopes and rock walls in the South-East Grampians, rock falls and snow avalanches merit special attention. Rockfalls occur in mountains of all latitudes. They are the most fundamental, most rapid, and simplest transport process on steep walls, yet their role in the post-glacial recession and modification of rock walls in Scotland appears to have been neglected.

ROCKFALLS.

8:1 Introduction

At the foot of most steep rock walls in the study area are developed extensive talus formations, supplied by rockfalls. Rockfalls are the main process of addition to screes (Young, 1972, p.131). Frequent rockfalls occur from the rock faces of the glacially oversteepened glens in the South-East Grampians (Clapperton and Crofts, 1969).

The recession of rock walls in the Karkevagge Valley in the northern Scandinavian Mountains seems, according to Rapp (1960), to have been rather restricted in post-glacial times, and has not exceeded more than a few metres. Similar conclusions have been tentatively drawn from short term observations in the Stuic Corrie of the Lochnagar Massif.

Ocassional visits to the corrie gave the impression that the rock walls were inactive, but a three week period spent living in the Stuic Corrie left no doubt as to the present day occurrence of rockfalls.

A description of the rock walls and their origin will aid the understanding of rockfall mechanisms in this area.

Rockfalls in the Lochnagar Corries

Intensive ice action eroded two large corries and one smaller corrie into the granite mass of the Lochnagar Massif, oversteepening slopes and leaving bare granite slabs and cliffs. The free-faces and other bedrock slopes exhibit parting-planes parallel to the outcropping surface, intersected by other sets of joints.

Parting-planes in elastic rocks, parallel to the ground surface, are known as topographic-jointing, pseudo-bedding, or sheeting, and were first explained by Gilbert (1904). Pseudo-bedding is exhibited under a wide range of climatic types (Ollier, 1969, p.5). Matthes (1930) was the first author to suggest that unloading, caused by glacial erosion, was a possible mechanism to explain the origin of such features in the granite valleys and corries of California. Subsequently Jahns (1943) used pre-glacial sheet structures as datum lines to estimate the minimum amount of glacial erosion at specific localities in New England. A number of workers have examined the significance of sheeting in the evolution of granite tors, especially on Dartmoor (eg. Waters, 1952; Linton, 1955; Palmer and Neilson, 1962; Waters, 1964). Recently, Sugden (1968) discussed the pseudo-bedding in the granite of the Cairngorm mountains but concluded that the pseudo-bedding he described lies parallel to all the main Cairngorm slopes, other than the glacial facets (p.81).

The parting planes observed in the Lochnagar granite accord with the descriptions of Matthes (1930) of closely spaced planes parallel to the walls of the corries. The concave exfoliation planes are believed to have developed as extension fractures, the rock expanding in the direction of minimum principal stress by fractures normal to it, as a result of the removal of overburden, and possibly ice load (Harland, 1957). Joint sets intersecting the pseudo-bedding and belonging to regional and local trends, are primary features,developed during the emplacement and cooling of the granite (Barrow and Craig, 1912, p.85). Together the cooling joints and sheeting provide planes of separation that are susceptible to penetration by water and frost. Through this agency blocks are loosened and detached. They slide down the pseudo-bedding planes, which provide steeply inclined sliding surfaces.

During the months of June, July, and August 1972, nine rock-falls were observed in the field, providing valuable information as to the frequency and size of falls.

1. 13 June 1972 A rockfall from the back-wall of the Lochnagar Corrie (NO 247857, aspect 47° magnetic) at 1106 B.S.T., dropped 4 large fragments and much small debris, totalling about 1 cubic metre, into a gully. The debris then bounced and rolled down the gully and out onto the scree apron. The sun leaves the face about 0930 B.S.T..

2. 13 June 1972 A rockfall from the free-face south of the Stuic Buttress in the Stuic Corrie (NO 226854, aspect

97^{o} magnetic) at 1402 B.S,T., released 2 granite blocks of about 00.25 cubic metre each onto a snowbank situated on a platform at mid-height on the face. One of the blocks slid for about 10 metres on its long axis down the snowbed before coming to rest. The other bounced and rolled down the snow, overshot the base, and fell a further 15 metres to the loch-side. The sun leaves the face about 1255 B.S.T..

3. 13 June 1972 At 1510 B.S.T. about 5 small rocks, up to lmetre long, fell down the cliffs south of the Stuic Buttress in the Stuic Corrie (NO 226854, aspect 97^{o} magnetic), onto the mid-height snowbed. They bounced and rolled, each sliding about 3-5 metres before coming to rest. The sun leaves the face about 1255 B.S.T..

4. 7 July 1972 A very large volume of rock, totalling about 2.53 tonnes, fell from the Stuic Corrie slabs below the Lochnagar summit ridge in the Stuic Corrie (NO 240855, aspect 285^{o} magnetic) at 1442 B.S.T.. The sun had been directed to the face for about 70 minutes before the fall, but the weather was partly cloudy and the sunshine was intermittent.

5. 8th July 1972 A rockfall from the Stuic Corrie slabs farther round to the south from rockfall 4 (NO 240854, aspect 287^{o} magnetic), fell at 1746 B.S.T.. The volume of debris was estimated to be about 1.5 times larger than the debris of rockfall 4. The sun first strikes the face at about 1330 B.S.T..

6. 8 July 1972 A second rockfall from the Stuic Corrie slabs (NO 240854, aspect 287^{o} magnetic) fell immediately after rockfall 5 and was thought to be triggered by the impact of the latter. Three large blocks with a total volume of about 1 cubic metre fell to the left of rockfall 5.

7. 26 July 1972 A large block of almost 0.5 cubic metre fell from the Stuic Corrie slabs (NO 240854, aspect 287^{o} magnetic) together with much smaller debris, at 1743 B.S.T.. It was a hot sunny day, the sun had been warming the face for about 250 minutes.

8. 29 July 1972 Many large fragments with a total volume of about 1.5 cubic metres fell at 1255 B.S.T. from the Stuic

Corrie slabs (NO 240855, aspect 285^{o} magnetic) before the sun had begun warming the face.

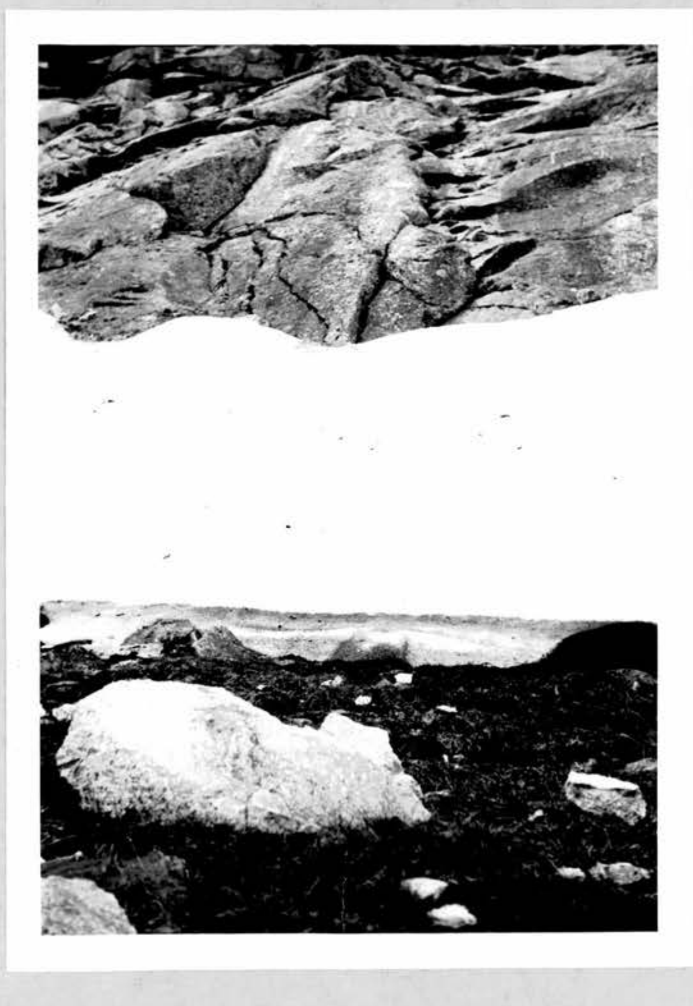
9. 1 August 1972 A clatter of falling rocks was heard to the right hand (west) of the Red Spout Gully in the Lochnagar Corrie (NO 254853, aspect 41^{o} magnetic). The corrie-wall was shrouded in mist when the fall occurred at 1315 B.S.T., and had been all morning. Several rocks fell below the mist level bouncing down the screes. The fall was intermittent and prolonged, lasting almost 1 minute.

All nine falls occurred between the hours of 11 a.m. and 6p.m.. Gardner (1969) concluded from observations during July and August 1966 that the most significant period of rockfall activity in the Lake Louis district of Alberta, Canada, was between the hours of 6-7 a.m. to 8 p.m.. There was a marked frequency of rockfalls between the hours of 11 a.m. to 3 p.m., the four 'maximum hours', during which period 58.88 per cent of the total occurred. Five of the nine falls in the table were in these four 'maximum hours'. Recordings from the Lochnagar massif were intermittent, and so probably only a sample of the total number of falls were observed, and observations were limited during the hours of dark and early daylight. Both of these problems were admitted by Gardner (1969, p.195).

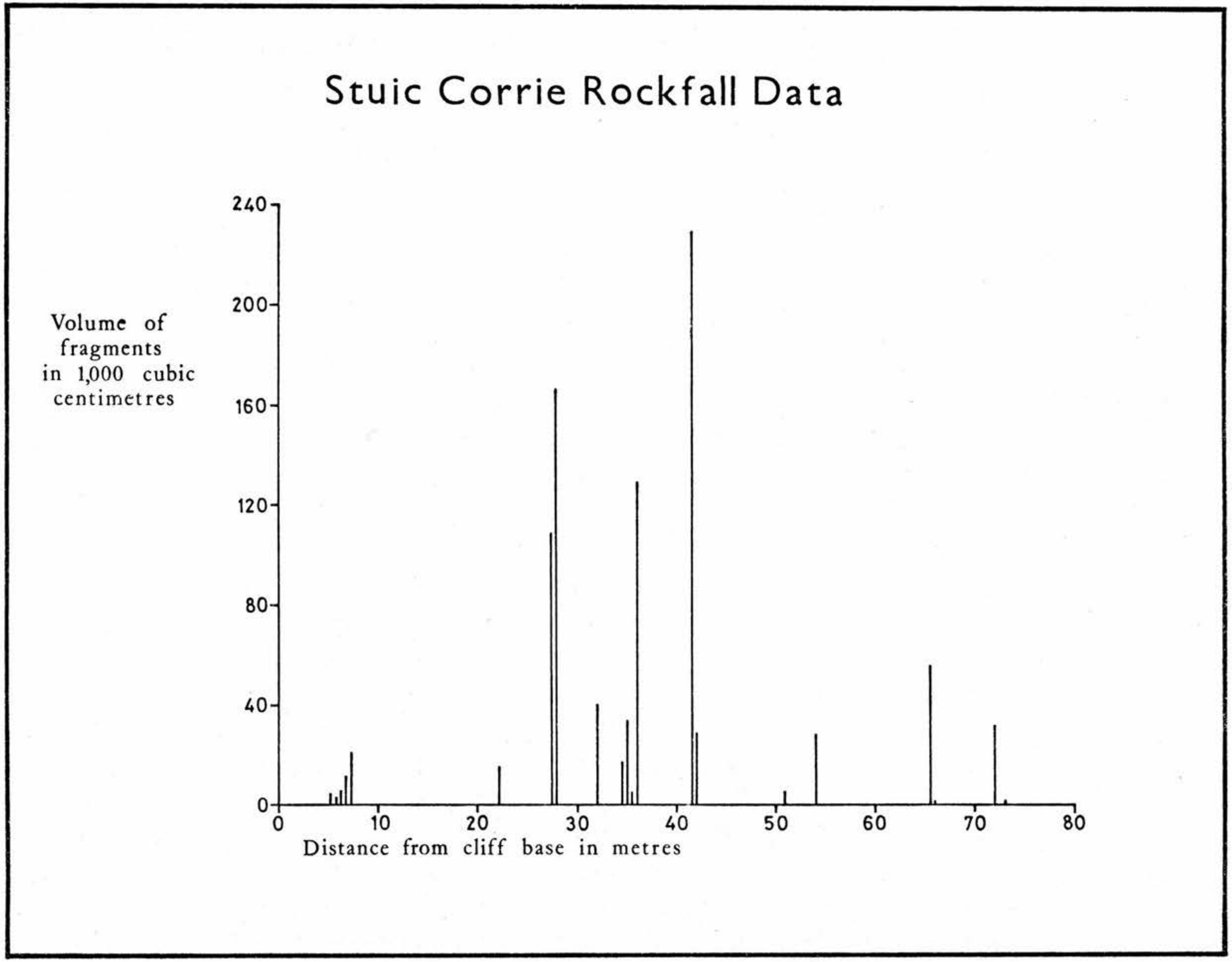
Rockfall(4) was examined in detail 24 hours after it took place. The released blocks had been seen to slide down the steeply inclined slabs (Photograph 8.1) and overshoot a snowbed at the base of the outcrop (Photograph 8.2). A large block hit the vegetated area at the top of the scree, leaving a deep impact scar (Photograph 8.3). Large blocks bounced down over the rocks of the scree, shattering, and creating showers of fine granite chips and plumes of powdered granite.

The distance travelled by each block from the base of the free face and their respective volumes are plotted in Figure 8.1. The diagram shows the largest blocks settled near the mid-point of the maximum distance travelled by the debris. Small debris at the top of the scree is considered to represent fragments produced by the initial impacts of the larger blocks, and that derived initially

PHOTOGRAPH 8.1 The Stuic Corrie slabs showing the basal snowpatch (s.p.) and the release area (R.) of rockfall (4).



PHOTOGRAPH 8.2 The snowpatch at the foot of the Stuic slabs, that was overshot by the blocks of rockfall (4). Fine fragments of the rockfall can be seen on the surface of the snow.



Stuic Corrie Rockfall Data
Volume of fragments in 1,000 cubic centimetres
240
200
160
120
80
40
0
0
10
20
30
40
50
60
70
80
Distance from cliff base in metres

Figure 8.1

from the source, whilst the smaller fragments below the zone of large blocks are considered to be fragments produced by later impacts of the larger blocks.

No further data were collected from this scree, as the descent of rockfalls (5) and (6) while measuring the blocks of rockfall (4) made continued working hazardous. Therefore data were collected from four other screes below free faces in the Lochnagar and Stuic corries to investigate the stone orientation and size distribution characteristics of screes supplied by rockfalls.

All four screes have concave longitudinal profiles. In all four the average block size is larger at the base than at the top of the scree (Table 8.A). Carrigy (1970) stated that the angle of repose of granular materials with similar surface characteristics increases with the departure of the grains from the spherical form. Angle of repose also increases as the fragments increase in size (Ollier, 1969, p.215). The measured screes have steep upper sections composed of smaller, more angular debris than the base, but the lower sections although composed of large blocks, have a low gradient. The high angle maintained at the top of the screes can be explained by the very angular nature of the debris there, and the shallow lower sections probably represent a pro-talus apron of larger blocks which have travelled farther down the scree over snowbeds coverihg the slopes, or by avalanche and rockfall from the slopes above. Rapp (1960) described a border of large boulders at the base of scree slopes, and Embleton and King (1968, p.561) explained that the larger rocks dislodged by slab avalanches roll farther down the slope than smaller ones. According to Young (1972, p.131) larger blocks travel further down the scree because they are less liable to be trapped in cavities, and also because volume, and therefore mass and momentum, increase as the cube of the diameter, whereas surface area and therefore friction only increase as its square.

This relation did not hold in the measured rockfall example (rockfall (4), Figure 8.1). The largest debris was near the centre of the new debris-train, and the maximum distance travelled by any block was only to the mid-point of the scree. All the blocks were seen to be resting in cavities between blocks of the scree

PHOTOGRAPH 8.3 A view down the scree from the snowpatch. In the foreground is an impact scar caused by rockfall (4), gouged in the turf fronting the snowpatch.

PHOTOGRAPH 8.4 The fresh debris (F) of rockfall (4) lodged between blocks of the scree and assuming various orientations.

TABLE 8.A

The Boulder Size Distribution in Four Granite Screes

	(a) The average length of 50 blocks cm	(b) The average width of 50 blocks cm	(c) The average thickness of 50 blocks cm	a x b x c The volume of the average block cu. cm
Stuic Corrie				
Scree 1				
Top	94.80	34.10	20.66	66,787
Centre	98.10	48.90	31.55	151,108
Base	94.22	59.00	40.60	225,695
Scree 2				
Top	63.52	38.52	23.60	57,744
Base	77.40	47.22	31.48	115,054
Lochnagar Corrie				
Scree 3				
Top	39.38	22.58	13.54	12,040
Base	64.20	43.84	28.88	81,284
Scree 4				
Top	49.46	24.54	16.10	19,541
Base	73.76	39.18	26.74	77,276

	map ref.	aspect	gradient	
Scree 1	NO 224853	020°	top	33°
			centre	27°
			base	12°
Scree 2	NO 247857	032°	top	35°
			base	25°
Scree 3	NO 229850	002°	top	32°
			base	19°
Scree 4	NO 237853	328°	top	28°
			base	21°

(Photograph 8.4). The larger blocks may travel farther if they fall onto snowbanks in winter and slide, as observed in rockfalls (2) and (3).

Stone orientation studies were carried out upon stones of the four screes, and composite diagrams constructed from the results of all four sites (Figures 8.2, 8.3 and 8.4).

Samples of 50 stones (Young, 1969, p.2348) were gathered, using 3 metre quadrats, at the top and basal sections of each scree. All the stones were loosely packed, a characteristic of avalanche deposits (Allen, 1972). The lack of any well defined orientations, as seen from the rose-diagrams (Figures 8.2, 8.3 and 8.4) agrees with the work of Gardner (1969) who found a varied orientation of stones from screes in the Rocky Mountains. Gardner saw a preference for a slight downslope orientation in some of his examples as did Caine (1969) in New Zealand. No such tendency is apparent in either of the four present examples, from the Lochnagar (Figure 8.3) or the Stuic (Figure 8.2) corries, in fact, no sample has a statistically significant mean orientation direction (L greater than 24.5% at the 0.05 confidence level).

The mean orientations and their strength in percentages were calculated using the methods described by Curray (1956). Lack of any significant orientation is possibly a result of the settling of blocks into available interstices, either being trapped after a rockfall (Photograph 8.4) or melting down from a snowcover, and suggests the present day inactivity of the screes, no down-slope mechanism working to re-orient the blocks. Caine (1969) performed detailed studies upon screes in New Zealand, and concluded that the random fabric patterns observed were to be expected, as they were a response to random processes of talus accumulation and creep, the work of completely random influences with no directional preferences when referred to the horizontal plane (thus excluding the vertical force of gravity). Slight downslope orientation near to the base of one scree was attributed to sliding processes, and a weak cross-slope orientation near the top to rolling being the dominant type of movement.

Rapp (1960) measured talus creep of up to 10 cm a year on

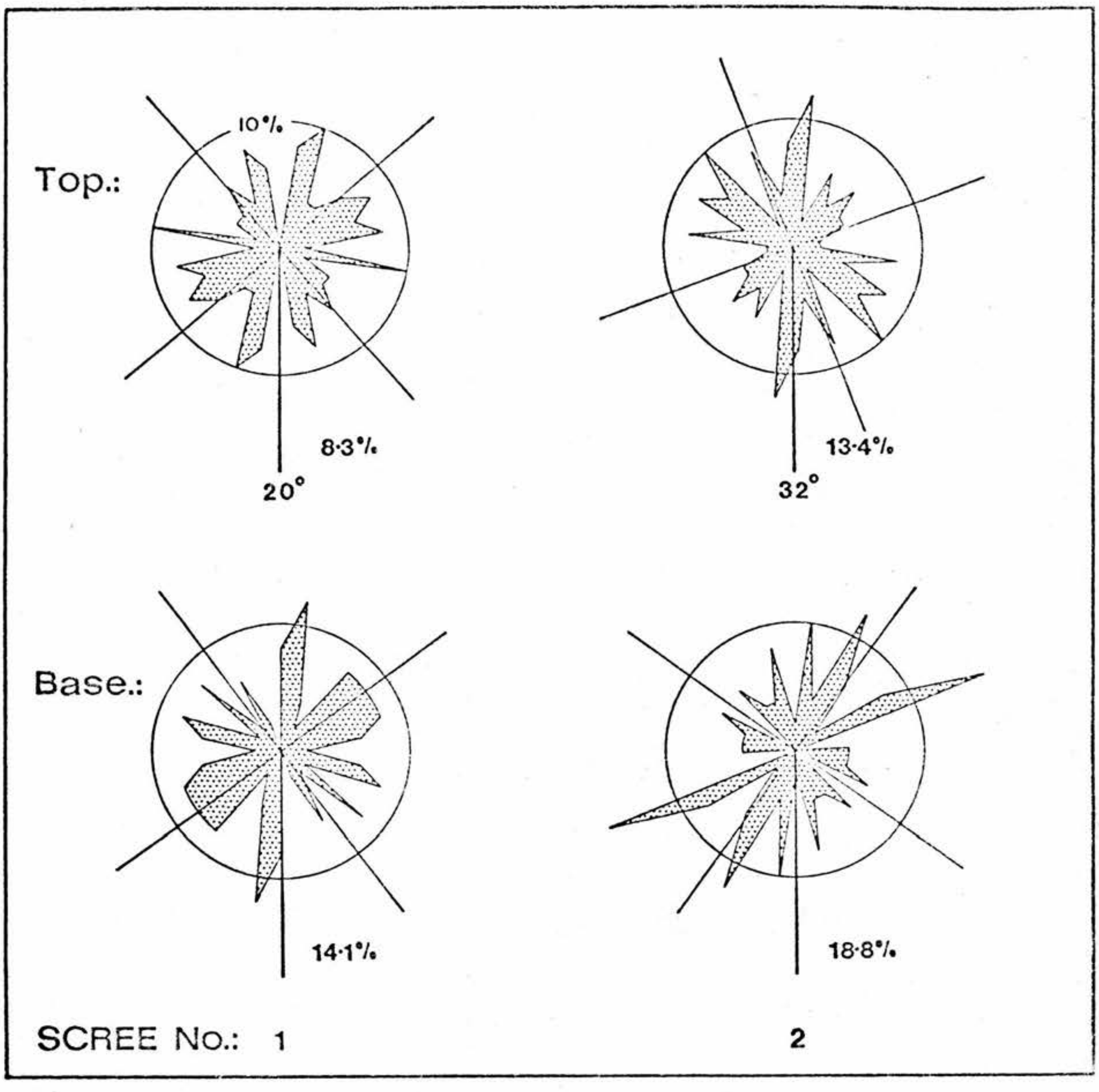


Figure 8.2

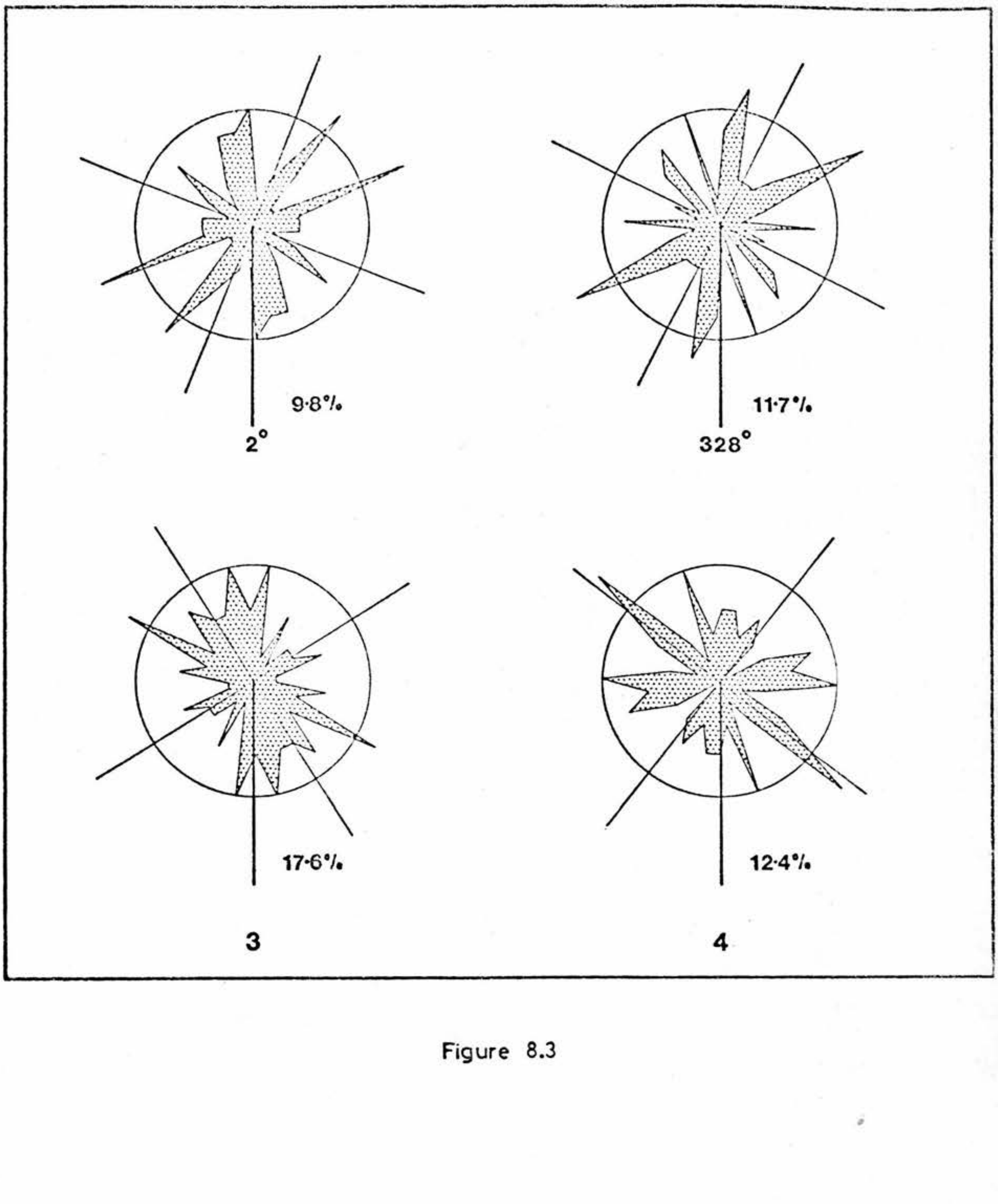


Figure 8.3

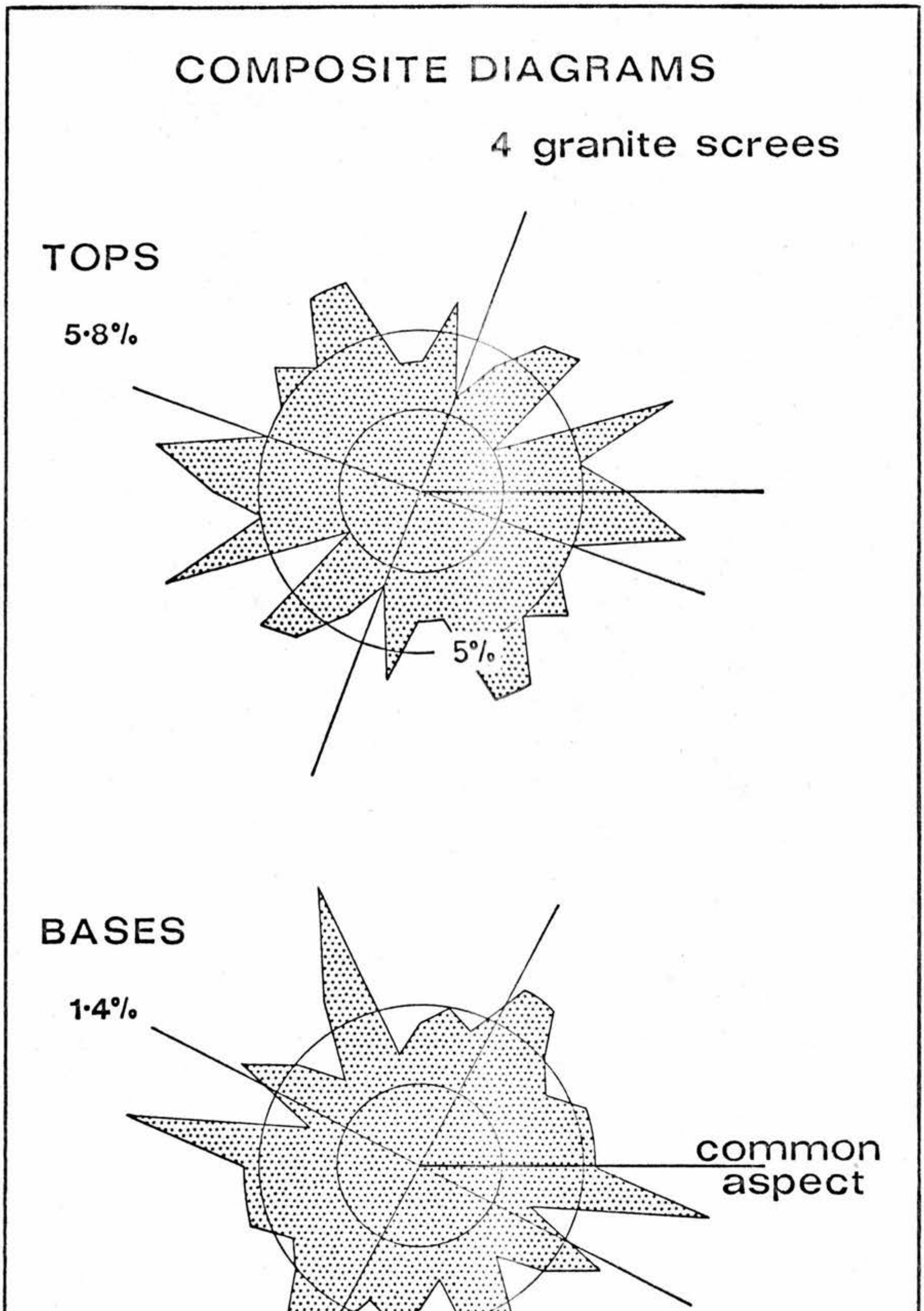

COMPOSITE DIAGRAMS
4 granite screes
TOPS
5·8%
5%
BASES
1·4%
common
aspect

Figure 8.4

screes in northern Scandinavia, but found no movement at their bases. He accounted for the movement by expansive freezing and thawing causing displacement of debris, and washing out of the fines allowing settling. Drewry (1973) observed that surface sliding was the dominant transport mechanism on undisturbed talus slopes in north-east Greenland. This was described as an open-system process triggered by an external disturbance of scree stability, the effects of rockfalls being to dilate the slope debris and create migratory voids in the material, causing failure. Ford and Anderson (1967) examined sorted talus aprons in Antarctica which moved by repeated thermal contraction and rupture of underlying ice. Gardner (1969) assigned measured talus movements in the Rocky Mountains to processes of subsidence, rolling, sliding, and true creep.

Thus a variety of mechanisms for moving debris on scree slopes has been reported. As no measurements of individual stone movements from the four granite screes are available it can only be inferred from the lack of downslope stone orientations (Lundqvist, 1949) that the stones are not now moving. Ollier (1969, p.215) suggested that the screes in many areas of the world are not active, but are relic formations resulting from periglacial conditions in post-glacial or periglacial periods. If ice occupied the corries during the Loch Lomond period (Sissons and Grant, 1972) and scoured out the loose debris, the screes must be of postglacial origin and so must have accumulated by rockfall and avalanche contributions in post-glacial times, with no further movement of the debris occurring since deposition.

Post-Glacial Cliff Recession and Rockfall Periodicity

Rockfall (4) produced a measured volume of debris of about 950.000 cubic centimetres, which represents a weight of about 2,530 kilograms (if the density of granite is assumed to be 2.67 grams per cubic centimetre (Read and Watson, 1962, p.13)) or 2.53 tonnes.

The total exposed sloping area of the slabs from which rockfall (4) originated was calculated from the Ordnance Survey 1:10,000 metric map to be approximately 40,500 square metres. If the material of the rockfall is distributed as a veneer over the whole face, then it is equivalent to a thickness of 0.024 mm being removed. Almost 42,000 such falls would be necessary to cause the cliff to receds by 1 metre, and so although each fall is impressive the effect of rockfalls on cliff recession is negligible.

Work by Rapp (1960) revealed that the annual average rockwall retreat in the Karkevagge valley of Northern Scandinavia is 0.06mm, or 0.3 to 1.0m during the post-glacial period. About 2.5 falls of the magnitude of rockfall (4) would be required to cause the Stuic Corrie slabs to retreat by 0.06mm. Rockfall (5) was estimated to be 1.5 times larger than fall (4). Rockfalls (4) and (5) together with the contributions of the lesser rockfalls observed from the Stuic Corrie slabs indicate that in 1972 these slabs reached a rockfall value almost equivalent to the Karkevagge valley.

The observations were limited to the small area of the Stuic Corrie, with a few cases from the Lochnagar Corrie. If the measured and estimated rockfall volumes were distributed over the whole cliff areas of the two corries, the results would be less similar to Rapp's figures. The spasmodic observation of rockfall incidences indicates that many falls must have occurred during the night or when the author was not present in the corries, the noted falls being only a few of many. Also the frequency maximum of rockfall activity is likely to be earlier in the year, coincident with the spring thaw. Rapp (1960) found that rockfalls could be correlated with thawing after frost bursting, the spring maximum occurring in May and June, and a minium in the winter months. The thaw period is likely to occur earlier in the year in Scotland, which means that the period of greatest rockfall activity was probably not observed.

Examination of blocks in the scree below the free faces in the Lochnagar and Stuic corries, with individual blocks up to 4 metres long, demonstrates that much larger falls must occur. Most of the granite blocks are weathered to a dull grey colour and have thick and extensive lichen coverings, but many are much fresher, indicating that they fell more recently. These blocks would have served to increase the average rate of rockwall recession if they had fallen during the observation period.

The rockfalls observed could not be associated with any one trigger mechanism. In the cases of falls (1), (2), (3), (5), and (7), strong sunshine on almost cloudless days had warmed the rock faces before the falls, and this could have thawed the frost loosened blocks from the face. Fall (4) was released on a grey cloudy day with only intermittent sunshine, fall (9) while the mist shrouded the cliffs, and fall (8) before the sun was directed onto the face. Animals such as sheep, foxes, or deer could have dislodged the small fragments of fall (9) from ledges on the cliffs, and warm air temperatures may have thawed the blocks of falls (4) and (8). Vibration caused by the impact of fall (5) is thought to have released rockfall (6) that occurred almost immediately afterwards.

It is very difficult to determine what mechanisms are responsible for releasing rockfalls. Prior, Stephens, and Douglas (1971, p. 136) correlated rockfalls in Northern Ireland with the occurrence of freeze-thaw cycles. The rockfalls observed in the Stuic Corrie occurred during warm periods, if not direct sunshine, with accompanying thawing of the extensive snowpatches in evidence, and so possibly were released when melting of ice veins was completed.

AVALANCHES

8:2

Avalanches are momentary mass movement mechanisms of mountain districts. They involve the rapid downslope transfer, by sliding, of snow, which may or may not be mixed with rock, soil, or vegetation debris.

In areas of the world with high mountains reaching well above the permanent snowline, and deep valleys hundreds of metres below the snow clad summits, avalanches have terrorised mountain people for centuries. Only in regions where the lives of people or the safety of their property are endangered, have steps been taken to gather detailed information concerning the distribution, mechanisms, and meteorological conditions of avalanche activity (Fraser, 1966; Atwater, 1968).

Very little mention has been made of avalanches in the geomorphological literature of the British Isles, with the exception of King (1968), and their existence has been ignored by most workers. Avalanches, until recently, only affected, or were observed by , a small number of people who lived in deep Scottish valleys or ventured onto the hills in Winter. One exception is a case cited by Fraser, (1966) of an avalanche at Lewes in Sussex that swept away a row of small cottages on the 27 December 1836, and buried 15 people, 8 of whom lost their lives. "There is an avalanche danger in Scotland and competent climbers should be able to recognise the signs and symptoms" (Tiso, 1967).

The hazards to life presented by avalanches, and notes regarding recognition of dangerous slopes are dealt with in many of the Scottish Climbing Guides (for example, Climber's Guide to the Cairngorm Area: Vol.II (Smith, 1962) in which the author details known avalanche tracks and avalanche precautions; and Smith, 1965; Fyffe, 1971), and general mountain safety procedures to guard against avalanche accidents are discussed in instructional manuals for the Alps (eg. Rebuffat, 1971), the Americas (eg. Grand Teton Natural History Association, 1958), and the Scottish Hills (Langmuir, 1968, 1969; MacInnes, 1969; Mountain Rescue Committee of Scotland, 1971). Information about the occurrence of avalanches in Scotland can be gained indirectly from descriptive articles of avalanche accidents (eg. Naismith, 1893; Raeburn, 1905; Tiso, 1968; Weir, 1972; MacInnes, 1973), eye witness accounts of avalanches (eg. Weir, 1973), selected from Scottish Mountain Accident Statistics (Humble, annually: see below), and from more technical articles concerning meteorology of the Scottish Hills (eg. Manley, 1972).

Table 8.B **Avalanche Reports**

Incidents involving avalanches have been taken from 'Scottish Mountaineering Accidents', statistics published annually in the Scottish Mountaineering Club Journal.

1955-1956		None reported
1956-1957	1.	Ben Lui: an avalanche near the summit carried down a party of four. 23 February
1957-1958		None reported
1958-1959	2.	Ben Nevis: number 2 gully, 2 climbers near the top of the gully, the new snow slipped with them from a base of old snow. 8 March
1959-1960	3.	Coire An t-Sneachda: cornice collapsed below a climber reaching top of corrie, carried him down and swept 3 climbers off the face. 29 December
	4.	Glencoe, Stob Coire nan Lochan: 2 climbers ascending coire, bad weather, heavy snow, high wind. Snow avalanched beneath them, swept into coire to near Lochan. 30 January
	5.	Glencoe, Stob Coire nan Lochan: 2 climbers ascending the right fork of Fork Gully, bad weather and deep snow. Leader avalanched and carried second down. 14 February

1960-1961 None reported
(only reported 1 April to 31 December)

1961-1962 6. Ben More, Stobinian: one girl descending to bealach, swept with snow down the steep corrie to the east, buried to neck in snow at bottom.

1 January

7. Buchaille Etive Mor: 3 climbers ascending last pitch of Crowberry Gully. Member avalanched, pulling other two off, carried 1000 ft..

8. Rescue team went up in bad conditions, two members avalanched for 160 ft..

7 January

9. Glencoe, Aonach Eagach: 3 traversing ridge, avalanched by powder snow, one member swept away. Body swept down 700 ft..

2 December

1962-1963 None reported

1963-1964 10. Ben Nevis: 2 persons avalanched.

24 December

1964-1965 11. 12. 13. 3 accidents occurred as a result of avalanches.

1965-1966 14. 15. 2 accidents by avalanche: areas not distinguished.

1966-1967 None reported.

1967-1968 16. Glen Affric, Mam Sadhail: member roping down a party, swept off by avalanche.

27 January

17. Creag Meagdidh Coire Ardair: 2 climbers on last pitch of Raeburn's Gully. Avalanche of new snow on old base, both carried 300 ft..

18 February

18. Ben Nevis, Steall Gully: Rescue team mamber and dog avalanched while searching for a lost walker.

2 March

19. Ben Nevis: 2 climbers in Number 3 gully, early afternoon, snow above them avalanched. Carried down 500 ft. on surface, then buried.

1 April

20. Buchaille Etive Mor: Search party looking for a lost walker in a hard snow blizzard, avalanched.

19 May

1968-1969 21. Coire Raibert: 4 rescuers avalanched searching for lost walkers.

3 January

22. Glencoe: 3 avalanched, breaking away of a wind slab, 2 came out early, other swept far.

6 February

23. Ben Nevis: climber in Number 4 gully swept down 300 ft. by a cornice fall avalanche.

18 March

1969-1970 24. Coire Cas: 3 parties at head of coire. 9 avalanched at steepest west side.

19 February

1970-1971 25. Ben Nevis, Tower Ridge: 3 people swept away and found dead in the avalanche debris.

18 January

26. Buchaille Etive Mor: new snow on hard base, conditions very dangerous. 4 people avalanched in Great Gully. 3 buried, one to 8 ft deep.

7 February

27. Ciste Dubh: soft snow over old ice, a party of 5 avalanched near the summit for 300 ft., one buried.

16 February

1971-1972 None reported

1972-1973 28. Ben Nevis: 3 climbers in Number 3 gully on a fine, cold day with no thawing, a slab avalanche from above carried them down for 500 ft..

1 December

29. Coire an t'Sneachda, Cairngorm: 2 climbers avaalanched and swept down for about 300 ft..

23 December

30. Corrie Fee, Glen Doll: 2 climbers avalanched while climbing the back-wall of the corrie.

29 December

1973-1974 The Scottish Mountain Accident reports not published.

Note: By the very nature of the reports only avalanches involving people are listed, and not all accidents are reportrd to the journal.

Langmuir was the first author to attempt a systematic study of snow conditions and avalanche development in Scotland (Langmuir, 1970), but his studies were restricted to the more practical aspects of saving lives using techniques pioneered in the Alps (eg. Fraser, 1966). No consideration, however, has been given to the geomorphological role of avalanches in Scotland (excepting King, 1968) similar to work in the Alps (Allix, 1924), Czechoslovakia (Vrba and Bedrich, 1957), Scandinavia (Rapp, 1959, 1960, 1962, 1964; Rapp and Rudberg, 1960), Spitzbergen (Dutkiewicz, 1967; Jahn, 1967), the Himalayas, (Inveronova, 1964), New Zealand (Caine, 1969a), and Canada (Potter, 1969; Gardner, 1969c, 1970; Luckman, 1971).

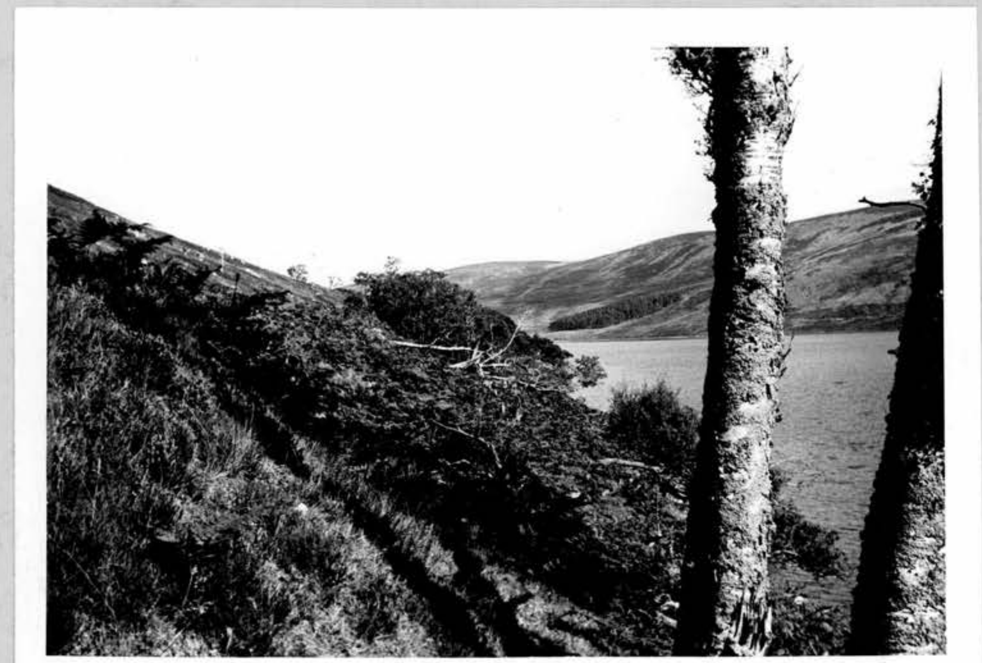
The need for safe ski areas, and later the protection of mountain mining settlements, was the stimulus which created and developed American avalanche research (Atwater, 1968) but little attention has been paid to the snow avalanche as a geomorphic agent (Potter, 1969; Luckman, 1971, p.95), prediction and control being the priorities. As man extends his installations into the mountains, protection from avalanches becomes increasingly necessary. Details of research projects to safeguard ski areas, lines of communication, and centres of population against the threat of avalanches have been described by Ives (1972), Schaerer (1969), Atwater (1968), and Fraser (1966).

Such awareness is needed in Scotland. Authorities concerned with recreational development in the Scottish mountains are promoting the first research centre to investigate Scottish snow and avalanche conditions (Langmuir - personal communication), but no investigations of their geomorphological significance have so far been reported.

The steep sided glacial troughs of the Lochnagar area have been described by Barrow and Craig (1912, pp. 116-118) and more recently by Sissons and Grant (1972), who noted the precipitous rock slopes bordering the troughs. "Snow avalanches are frequent down both sides of Loch Muick, as elsewhere in the Highlands, yet they remain blissfully ignored by many" (Watson, 1972, p.11). Each year avalanches cross the estate road on the south side of Glen Muick, blocking or gullying the road. The north side of Glen Muick exhibits clear evidence of at least three avalanches.

Two tracks approximately 180m and 100m wide respectively, and about 0.4 kilometres long, pass through a belt of trees bordering Loch Muick and the estate road to the Royal Lodge of Glas Allt Shiel. The trees are snapped off near their bases, bent and laid down towards the loch. (Photographs 8.5 and 8.6, 8.7 and 8.8). At the end of the tracks, in the loch can be seen fans of debris, the submerged avalanche tongues which contain small trees among the rocky debris. At the head of Loch Muick evidence of a third avalanche is visible. A large boulder weighing approximately 10 tonnes was buried to one third of its height in the slope debris below the crags at map reference NO 268827. A snow avalanche released from the crags dislodged the boulder and carried it 4.9 metres downslope, depositing it upon other boulders with its base 95 centimetres above the ground (Photograph 8.7). These avalanches are reported to have occurred in the winter of 1958/1959. The first two tracks through the trees are immediately recognisable, the third avalanche is less easily identified and was pointed out to the author. As can be seen from Photograph 8.8,

PHOTOGRAPH. 8.5 The eastern avalanche track on the north side of Loch Muick, showing the flattened birch trees.



PHOTOGRAPH 8.6 The western avalanche track by Loch Muick.

PHOTOGRAPH 8.7 The granite block moved by a snow avalanche in the winter of 1958/59, perched upon blocks 95cm above the ground.

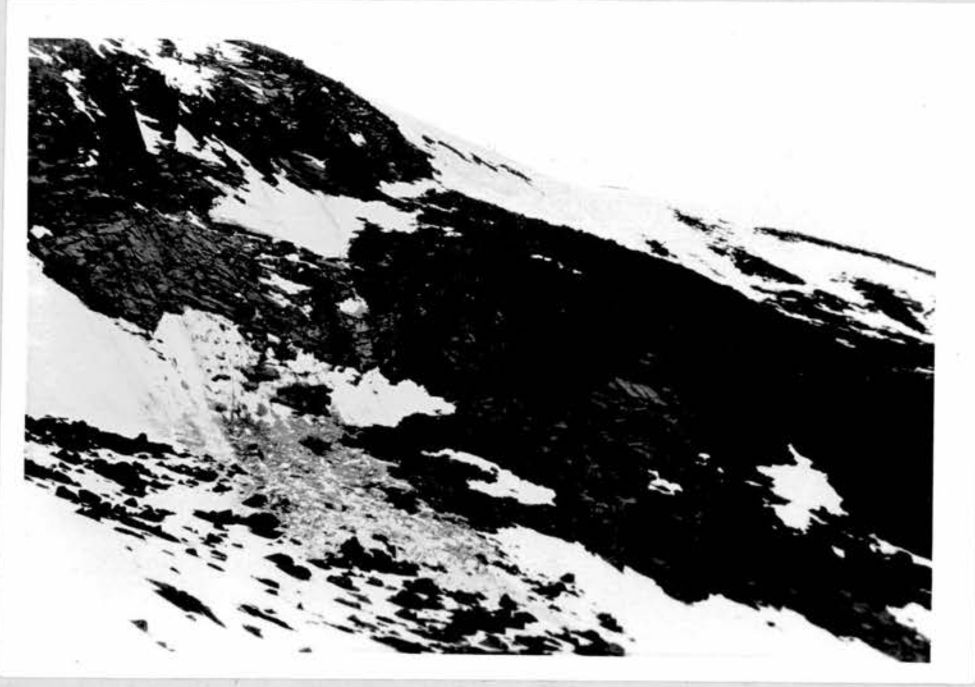
PHOTOGRAPH 8.8 View from the crags, bordering the north side of Glen Muick, down the debris slope to the avalanche moved granite block.

the block is perched upon the flank of a morainic hummock bordering the valley side, and could be mistakenly interpreted as an original ice deposited feature. Frequent rockfalls descend this slope, which is littered with granite debris from the cliffs above (Photograph 8.8), and numerous fresh scars in the turf indicate where falling blocks have bounced.

It is usual for the prevailing south-westerly winds to promote snow accumulation and cornice development above the north facing slopes bordering Loch Muick, blowing it from the extensive high level (around 680m) moorlands of Creag Bhiorach and Black Hill (753m). In the winter of 1958/1959 a long period of north-easterly winds caused avalanching on south and west facing slopes. Small avalanches descended the south and west slopes of Glen Clova early in 1973(Colin Miller - personal communication) from collapsed cornices, built up by a period of constant north-easterly winds. Similarly, winds from the north-east quarter in 1947 caused snow build-up above Glen Clova, when a large herd of red deer sheltering in the Kitchy Burn (NO 283795) were overwhelmed by a snow avalanche, and again in 1953 a herd of over 20 red deer were dismembered by avalanching of snow from Red Craig (NO 300750) at 646m.

Extensive cornice development in the north-east facing corries of Lochnagar, the Stuic Corrie and Corrie Fee give rise to frequent avalanches. A very large cornice fall in the winter of 1965/1966 in the Stuic Corrie produced a debris of snow blocks on the corrie floor. Individual snow blocks were as much as 6m high. Above Glen Doll in Corrie Fee (NO 250750) in the winter of 1972/1973, two climbers were swept off the back wall of the corrie by an avalanching cornice.

The contribution of snow to the north-east facing corries, swept from the high level moorlands by the prevailing south-westerly winds would have had important consequences in late glacial times when glaciers occupied the corries and the plateaux were free of ice (Sissons and Grant, 1972; Sissons, 1972). Contemporary evidence of avalanching into the corries, sometimes on a large scale, at other times as small slides (Photographs 8.9 and 8.10), suggests that in times of a more severe climate with



PHOTOGRAPH 8.9 A dirty snow slide from steeply sloping granite slabs in Coire na Cive. NOTE: the tension rift near the crest.

PHOTOGRAPH 8.10 A close-up view of the tension rift illustrated in the previous photograph, showing the steep back wall and the pressure ridges below the rift.

an increased snowfall, large volumes of snow could have been provided by this mechanism to nourish corrie glaciers in the Stuic Corrie, Lochnagar Corrie, and Glen Muick, as described by Sissons and Grant (1972, p.92) and Corrie Fee, described by Sissons (1972).

Present day avalanches endanger the lives of people on the hills in winter, are capable of destroying tree belts, young plantations and fences (two successive forestry fences in Glen Clova have been torn out by snow avalanches), blocking and eroding roads, and killing economically valuable deer herds. The landscape sculpturing effects, observed in areas of the world with a large relative relief, are not present in Scotland, but recognition of the occurrence of avalanches and their powers of destruction has shown that they are not an agency to be ignored or lightly dismissed.

In summary it would be valuable to examine the general avalanche patterns in Scotland in relation to weather conditions throughout the seasons (after Langmuir, 1968).

Scotland has a relatively low snowfall, with individual falls of less than 0.6m, and shorter slope lengths than the more mountainous countries, and so avalanches are less frequent and not as widespread as in areas of the world that possess these characteristics. For these reasons the massive Alpine-scale avalanches cannot occur in this country.

Several factors operate to work against the above restrictions. Wind redistributes snow into gullies and onto lee slopes where enormous depths can accumulate in the form of thick snow cushions, wind slab or cornices. This helps to reduce the area of slopes from which avalanches are likely, and points to the areas where precautions are necessary (Atwater, 1968). Soft slab avalanches commonly descend from lee slopes either during or very soon after a snowstorm, and hard slab avalanches can be expected after a longer period, especially if conditions remain cold.

The very rapidly changing weather pattern characteristic of the climate of the United Kingdom, exhibits relatively high winter temperatures and a very rapidly fluctuating freezing level. These features of the climate decrease the possibility of avalanching by hindering the accumulation of snow through their effect om promoting settling and firnification, but encourage the development of crust layers produced by the wind, sun, or melting and refreezing. Such crusts are a potential source of avalanche danger when covered by new snow falls or wind-transported snow.

Rain can fall in any season. Spring snow is little affected by rainfall, but unstable conditions can be produced by rain early in the year, increasing the weight of heavy snow slabs that have a poor attachment to the underlayer.

The protracted springs typical of the British climate usually give rise to only small falls of snow. Snow remaining from the winter is characteristically well consolidated and sugary, and survives on hill tops and in gullies. It is uncommon for wet snow avalanches to occur in the spring, which is not the case in the Alps where the violent thaws cause massive wet snow avalanches (Fraser, 1966), and also in Spitsbergen and the Arctic where spring slush avalanches are a major landscaping agent; (Jahn, 1967; Washburn, 1973). Avalanches of old snow are likely in the spring after percolating water has weakened their attachment to the ground. Spring avalanches of old snow frequently descend the same tracks each year, and become well known. They are usually due to some local peculiarity of the situation that favours their release. One of the most notable examples is the Coire an Lochan avalanche in the Cairngorms, which occurs every year in early May (Smith, 1965, p.129; Langmuir, 1968, 1969; MacInnes, 1969). Spring melt water is responsible for breaking the bond between a large slab of old snow up to 8m thick, and 180m long, and the sheet of smooth granite slabs upon which it rests.

There exists a whole unexplored field of research into the quantitive transportational activities and sculpturing effects of snow avalanches and their frequency, and the frequency and volume of rockfalls in this country.

Such studies would require careful observation and recording over several seasons, as begun in Canada, by Gardner (1969b, 1970). It is likely that the results would have important consequences for our interpretation of rock wall and mountain slope development in Scotland, and the description of present day Highland landforms.

CHAPTER 9

Boulder Weathering Studies

Introduction

The margins of the last glaciers in the Scottish Highlands, as far as they are known, have been delimited by subjective studies of glacial deposits and features, upon aerial photographs, and in the field. More recently the objective technique of pollen analysis has assisted the definition of glacial limits wherever suitable organic accumulations exist to permit sampling. This technique is especially useful in wide valley situations where no definite moraines are present and only irregular drift limits occur accompanied by peaty and marshy hollows. The scoured and boulder strewn landscape around the high level corries of the south-east Grampians yields few sites suitable for pollen investigations. There is, therefore, a need for further objective techniques which are capable of differentiating between bouldery deposits of different ages, situated upon the 'inside' and 'outside' of the corrie moraines.

Preliminary investigations of the nature of the boulder debris scattered over the surfaces of the Lochnagar and Mount Keen granite massifs indicated a difference in both the angularity and the degree of surface weathering of granite boulders occurring 'inside' and 'outside' the corrie moraines. These observed differences were the subject of detailed investigations to establish methods for measuring variations in the degree of weathering. If such differences could be measured then a further technique would be available to use in granite areas where the margins of former glaciers could not be confirmed solely upon the basis of marginal glacial deposits.

The first and least accurate technique was that used in the initial reconnaissance. This was a visual assessment of angularity, a purely subjective technique. As a supplement to the visual assessment of rounding, a template former was used to measure the amount of rounding of the edges of the granite blocks. A scale of rounding was constructed so that results from different areas could be compared.

The degree of weathering of the surfaces of the boulders was determined by the third technique. This method allowed classification of the extent to which subaerial weathering had affected the faces of the boulders. The results were expressed as 'Granite Weathering Ratios'.

Finally, an attempt was made to examine the extent to which weathering processes had affected the surface layers of the granite boulders. Tape recordings were made of the sounds emitted by boulders when hit with a hammer. As the coherence of the granite crystals is destroyed by intergranular weathering, the sound transmitting characteristics of the boulders would be expected to alter as the weathering progressed. The changing characteristics of the recorded sounds were established and this enabled broad weathering categories to be identified.

Aims of the Study

The purpose of these investigations was to examine the possibility of establishing a relative chronology based upon differences in the degree of development of selected weathering characteristics of granite boulders occurring 'inside' and 'outside' the presumed limits of the last corrie glaciers. If characteristic differences could be determined, then similar studies would provide a useful research technique in areas where glacier margins are indefinite, or where the limits of multiple glaciations require to be identified and separated. Additionally, if measurable differences are demonstrable, the technique would independently support the view that active corrie glaciers have occupied the corries since the time an ice-sheet covered the area.

Bases of the Techniques

Each of the four weathering studies that were undertaken is based on the assumption that end moraines represent the limits of the clearing out (by glaciers) of a formerly weathered land surface (Birman, 1964). Consequently any boulders occurring 'outside' the moraines, or presumed limits of the last glaciers, will have been exposed to subaerial weathering for a longer period than those situated 'inside' the limits; conversely, all boulders occurring within the glacial limits are presumed to be relatively freshly derived.

Exceptions to this general rule do occur. Boulders prised by glacial-action from the pre-glacially weathered corrie floor or rock walls may be finally deposited within the glacier limits. Similarly rock-fall debris from the corrie walls deposited on the glacier surface may also be left within the glacier limits. Post-glacial rock falls and avalanches contribute 'weathered' to completely fresh rocks to the corrie floor in a zone of variable width below the corrie walls (see Chapter 8).

The corrie moraines are assumed to be composed of the pre-glacially 'weathered' debris scoured from the corrie floor combined with fresher granite derived from the corrie floor and corrie walls. For this reason the end moraine zones were not sampled. Examinations were restricted to boulders occurring in areas away from this marginal zone, and away from the rock-fall and avalanche zone. Sampling areas were selected in order to record as far as possible only the weathering characteristics of boulders in situations away from the areas covered by corrie-glaciers, and those in areas certainly covered by corrie glaciers but uninfluenced by the moraine zone and rock-fall and avalanche zone.

The weathering studies were restricted to the granite rocks of the Mount Keen and Lochnagar intrusions. This allows a simplification of the analyses as it has been assumed that the granite rocks from different parts of the area weather in a similar manner and at a similar rate. Thus all the results can be directly compared.

Subaerial weathering processes affect granite boulders most vigorously at the sharp corners and edges (see below), tending to round off the originally angular forms derived by mechanical weathering. Weathering also affects the boulder faces, causing them to disintegrate and slowly shed individual crystals, crystal clusters or small plates. Water penetrates any planes of micro- or macro- separation present in the boulders, and causes rock fabric below the surface to decay. It is these three basic weathering characteristics, the amount of edge and corner rounding, the extent of surface decay and the degree of sub-surface decay, which the present study seeks to measure and classify.

The variations in the frequency of occurrences within the different weathering categories, between different areas, were expected to provide information about the relative differences between the length of time each group had been exposed to sub-aerial weathering.

Granite Weathering and the Effects of Fires

Several terms exist that refer to the disintegration processes of granite and other igneous rocks. Granular disintergration is the decay of the rock fabric by breaking into individual grains(Ollier, 1965, p.295). Flaking is the shedding or spalling of scales of 'weathered' rock from the surfaces of boulders situated above ground level (Ollier, 1965, p.297). The term exfoliation has been reserved (Ollier, 1965, p.291, 1967, p.104) for the subsurface process, also often known as spheroidal weathering. Flaking refers to 'onion skin' weathering processes where flakes of rock about 1cm thick are shed from the subaerial weathering surface (Ollier, 1965, p.293).

In cold climates granite eventually disintegrates to a coarse sand or granitic gravel. The depth to which weathering processes can penetrate a granite boulder or solid outcrop is determined by the depth to which water can easily penetrate fissures in the rock (Raguin, 1965; Martini, 1967). Granite, in common with many other igneous rocks, frequently weathers by scaling off along the faces of joint blocks. This process is especially pronounced at the corners and edges formed by intersecting joints, thus producing the rounded boulder like forms commonly observed (Chapman and Greenfield, 1949, p.407). The thickest spalls are often found at the sharpest corners (Emery, 1944)

Usually the spalling of scales is due to the processes of hydration, carbonation or oxidation of individual minerals, which cause them to expand and contract differentially, and to frost-action, the freezing of interstitial water. Eventually the result is the seperation of the weathering layer.

Ollier (1965) pointed out that the flaking processes are most noticeable in hot areas (of Central Australia) and to a lesser extent in humid and colder areas. He believed that in very cold areas frost weathering produces angular blocks and flaking is absent (p.293). Hsi-Lin (1961, p.308) on the other hand, believed subaerial 'exfoliation' (flaking) forms can be found in tropical, temperate and also polar regions (Northern Norway).

According to King (1968, p.23), no 'exfoliation' (flaking) spalls are at present around granite boulders of high plateau felsenmere in the Western Cairngorm Mountains. Similar conclusions were drawn from the present studies, although very fine platey fragments easily detached by the finger nail were observed upon the surface of some well 'weathered' granite boulders. The flakes observed were usually only a few grains thick (up to about 0.5cm) and only up to about 5cm long. In very few cases, where well 'weathered' boulders were sampled (see the Granite Weathering Ratios section), did flakes occur numerously upon a boulder surface, or were they longer than about 0.5cm, or thicker than about 0.5cm. It appears that the granite boulders of the study area are weathering dominantly by the process of granular disintegration.

Spalling, or flaking, has also been attributed to the sudden intense heating produced by brush fires. Forest fires are frequent occurrences in the semi-arid forested mountains of the Western United States. Blackwelder (1927) ranked fires first in causing the disruption of boulders and rock outcrops in these areas. Experiments showed that many igneous rocks can withstand repeated sudden heating and cooling through more than 200°C without damage, but they begin to fail between 300°-375°C with such treatment. Acid granites and quartzite were found to be the most resistaht rocks, enduring slow temperature changes up to 800°C. Emery (1944) reported that brush fires were also capable of causing spalling of igneous rocks. After a large brush fire in San Diego County, California, quartz diorite boulders showed fresh spall surfaces, with up to 50% of the original surface of many boulders exposed as fresh white rock beneath the fire blackened surface. Ollier (1967, pp.103-104) pointed out that the effects of fire were quite different from most other small scale exfoliation. He described the spall fragments with curved inner surfaces and sharp edges and up to several centimetres thick at their widest part. The most characteristic effect was that only one sharp fracture plane was formed by fire, there being no succession of concentric surfaces as seen in other exfoliation forms.

As fires have been shown to be capable of causing spalling of igneous rocks, it was felt that the heather burning practices of the sporting estates could cause anomalies in the weathering study results if some of the sampling areas were regularly burnt over. Consequently the extent and nature of heather burning, or muirburn, was investigated.

Heather burning is generally less frequently carried out on the higher altitude moors (Miller et al., 1966). Observations in the field and interviews with the estate gamekeepers confirmed this general rule. The highest burnt moor on Lochnagar Hill was the Monelpie Moss at around 700m (map ref. NO. 275838). This was well below the areas sampled in the present study. Burning did occur over the sample areas of Mount Keen. Recently burnt strips were visible both upon the slopes of the Gathering Cairn (map ref. NO. 418887) and on the floor of the Corrach of Mount Keen (map ref. NO. 407877).

Whittaker (1961) studied the intensity of heath fires on the Glentanar Estate (Mount Keen). The results of the investigations revealed that the most frequently recorded temperatures were between 300°-500°C. The maximum recorded temperature was 840°C, and the minimum was 220°C. Temperatures at 20cm above the ground surface, at the top of the ground stratum of vegetation, were recorded as reaching up to 500°C higher than at the soil surface.

It is evident from these results that the temperatures occurring during heather burning, 220° to 840°C, are almost identical to those reported as occurring during forest fires, 200°-800°C (Chapman and Greenfield, 1949, p.415).

Figures are unavailable for the duration of high temperatures under forest and brush fire conditions, but it can reasonably be assumed that they will remain high for some time because of the nature of the material involved, thick tree trunks and brush stems. The higher temperatures during heather burning persist for only a very short period, and are not usually sufficient to kill the seeds, and only usually succeed in charring the heather stems (Whittaker, 1961).

Careful investigations over several of the recently burnt strips showed that no blackening of any of the boulders had occurred similar to that caused by forest and brush fires, and no fresh spalls were seen. In fact, as stated earlier, weathering spalls were almost completely absent from all granite rocks in the study area. It thus seems likely that the muirburn practices have very little or no effect upon the weathering of granite boulders in the Mount Keen study area. Nevertheless the possibility needs to be borne in mind and may prove worthy of further more detailed investigation.

Very little information is available regarding the rates of weathering of granite . Dahl (1967) measured the amount of post-glacial micro-weathering of granite bedrock surfaces in the Narvik district of Norway. He found a distinct tendency of the weathering values to increase from 0-120 m.a.s.l., and then to decrease from 120 to 500m. No particular trends were apparent above 500m, except perhaps for a general decrease in deterration (micro-weathering and the removal of weathering products) with altitude. The maximum rate of weathering, at about 120m, averaged about 1.28mm per 1,000 years. The rate at 85-95m averaged 1.05mm per 1.000 years. These results are of a similar order to those reported for granite rocks in the hot dry climate of Egypt (Barton, 1916). The rate of disintegration of granite was estimated to be about 0.5 to 0.8 cm per 5,000 years (1.0 to 1.6 mm per 1,000 years).

The rate of weathering of the granite rocks in the south-east Grampians study area is likely to be similar to the rates determined in Norway, that is around 1mm per 1,000 years. Thus it is to be expected that the amount of weathering accomplished during the post-glacial period will be small, and any detectable differences between 'inside' and 'outside' moraine situations will be of a low order.

Fragment Size Terminology

The present study is concerned with detached fragments of granite ranging in size from about 0.25m maximum dimension to 3m or longer. These fragments belong to the sedimentary category of boulders (longer than 256mm : Pettijohn, 1957, p.19; Tennissen, 1974, p.282).

In the present weathering study all the fragments sampled were of boulder size. They are referred to variously as boulders and blocks, the terms being used interchangeably. Neither term is intended to convey any genetic implications (as has been suggested, for example, by Lane *et al.*,1947).

Sampling Procedures

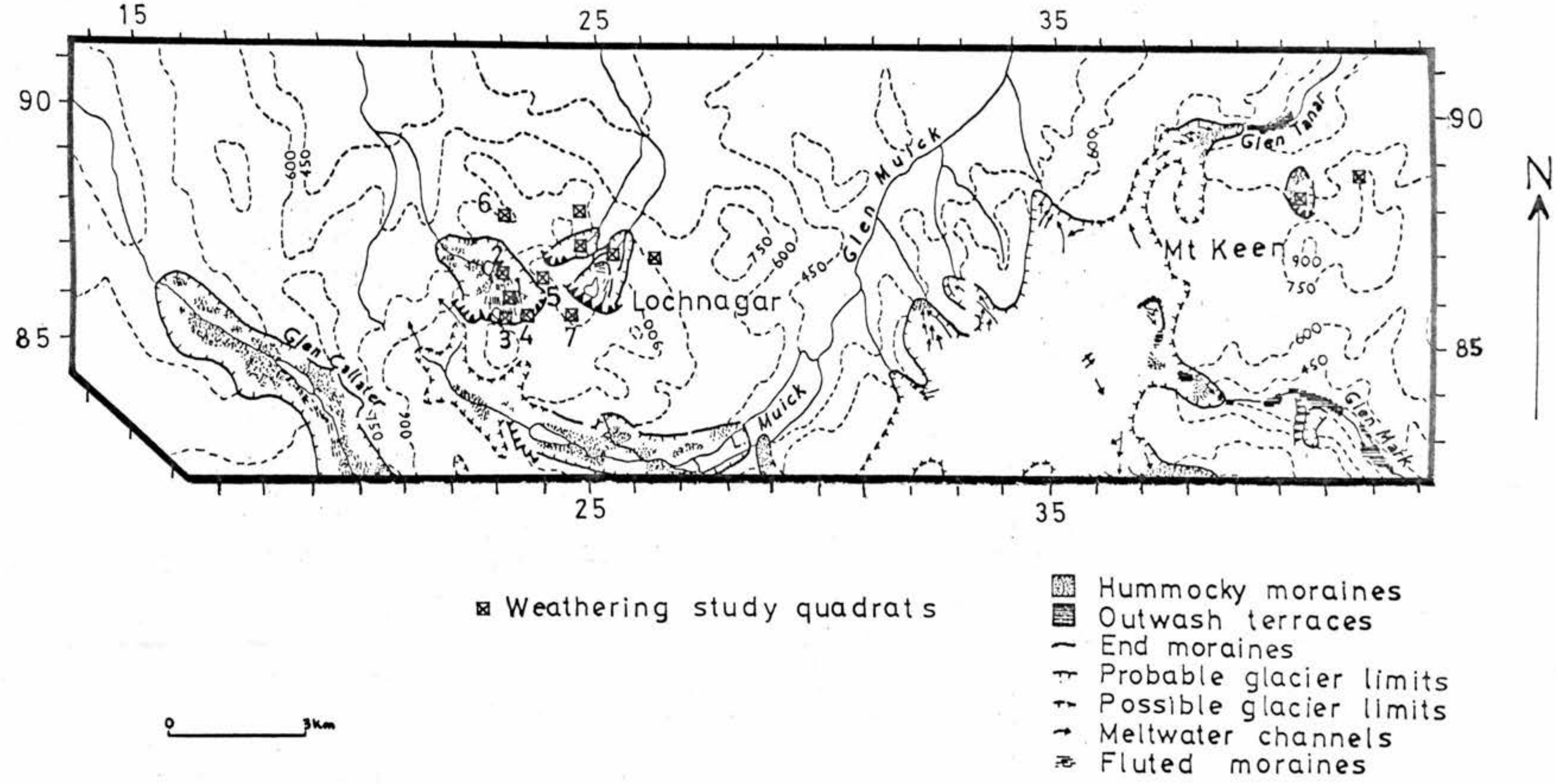
A quadrat sampling method was employed. Boulders were sampled at intervals of ten paces along a linear transect extending for 100 paces. A return transect was then made, parallel to the first and at ten paces from it. Similar transects were repeated to build up a grid pattern. The transects were often somewhat distorted or irregular due to the uneven nature of the terrain and the presence of large boulders which had to be detoured. The process of crossing the corrie floor often required stepping from boulder to boulder, thus the measured boulder frequently was the one upon which the observer landed. In cases where a tenth footfall was made upon vegetated ground the nearest boulder forward of the final position was sampled.

Quadrats 'inside' the moraines were placed close to the geometric centre or medial line of the corrie floor, and those 'outside' were placed upon suitably boulder strewn areas close to the limits.

Each of the three corries of the Lochnagar massif, and the Mount Keen corrie were investigated. All four weathering study techniques were applied in each case. Two independent samples were taken from 'inside' the Stuic Corrie to test the reproducibility of the results. Similarly three independent samples were taken from sites close 'outside' the Stuic corrie glacier limits including one from the summit ridge of the Lochnagar massif, and one from below the col between the twin summits of Lochnagar.

In addition two screes below the back wall of the Stuic corrie were sampled to allow comparisons to be made with the 'inside' and 'outside' situations.

Sample		Location of site	Approx map ref.
Stuic 'Inside'	1	Stuic Corrie floor	NO 232858
Stuic 'Inside'	2	Stuic Corrie floor	NO 233864
Stuic Scree	3	Stuic Corrie backwall scree	NO 232850
Stuic Scree	4	Stuic Corrie backwall scree	NO 238853
Stuic 'Oitside'	5	A lobate boulder area in the summit col.	NO 243858
Stuic 'Outside'	6	A lobate boulder area on the flanks of Meall an Tionail	NO 223874
Stuic 'Outside'	7	A lobate boulder area on the southern flanks of Eagle Ridge	NO 243854
Lochnagar 'Inside'		Lochnagar Corrie floor	NO 254864
Lochnagar 'Outside'		the lower eastern slopes of Meikle Pap	NO 264863
Coire na Cive 'Inside'		Cive Corrie floor	NO 247867
Coire na Cive 'Outside'		the north eastern slopes of Meall Coire na Saobhaidhe	NO 245876
Mount Keen 'Inside'		Mount Keen corrach floor	NO 407878
Mount Keen 'Outside'		a lobate boulder area on the western slopes of Gathering Cairn	NO 420885



Map Figure 9.1 The location of the sampling quadrats for the boulder weathering studies

All the sampling for each of the four studies was carried out in these general areas. This restriction was imposed in order to minimise any possible variations resulting from minor differences in the grain size of the granite, or differences in the weathering micro-environment due to differences in the aspect or exposure of the sites. The possiblity of such differences requires to be tested more fully: it was considered to be beyond the scope of this present study, but the two 'inside' and three 'outside' samples from the Stuic group were taken to act as a guide to any such possible areal variations.

The weathering studies were considered as two distinct groups: the two studies of boulder roundness characteristics, and the two studies of boulder disintegration.

9.1 Studies of Boulder Roundness

Introduction - The Roundness of Clastic Fragments

Roundness is a concept that relates to the sharpness of the edges and corners of a clastic fragment. It is independent of the shape of the fragment (Pettijohn, 1957, p.57). As roundness increases the radius of curvature of the edges and corners of the fragment increases.

Roundness is obtained by measurements taken in one plane only, whereas sphericity (shape) is a three-dimensional concept (Wadell, 1932). A fragment may possess a maximum degree of roundness and still not be a sphere, or have a high degree of sphericity and no roundness.

Rock fragments are non-spherical, highly irregular and defy ordinary geometric shape classification. Nevertheless, many techniques have been devised that attempt to describe the shape and roundness characteristics of clastic fragments. The primary factors that control these shape and roundness characteristics are (after Krumbein and Pettijohn, 1938, p.278)

1. The original shape of the fragment.
2. Structure of the fragment, such as cleavage or bedding.
3. The durability of the material, which in turn is a vector property of the rock or mineral fragment.
4. Nature of the geological agent.
5. Nature of the action to which the fragment is subjected and the violence of that action (rigour)
6. The time or distance through which the action is extended.

For the purposes of the present study the structures of the fragments, the durability of the material, and the nature of the geological agent are taken to be the same in all cases. The original shape of the fragments will vary somewhat, but all are assumed to be angular at the onset of subaerial weathering. The action of the subaerial weathering processes is similar in nature over the area, but perhaps differs slightly in intensity (rigour) in different topographic situations depending upon aspect and exposure. It is the final factor, the time through which the action has been extended that is the variable whose influence is investigated in the following studies.

Many techniques, of varying complexity, have been proposed for classifying the roundness characteristics of clastic fragments (see Krumbein and Pettijohn, 1938; Pettijohn, 1957), but none have been designed specifically for boulder sized fragments. The techniques of visual assessment of angularity, and the planar measurement of the radius of edge curvature were attempted in these studies.

9.1a. Visual Assessment of Boulder Roundness

Introduction and Previous Work

The assessment of the roundness characteristics of clastic fragments by visual inspection is a well recognised and long established technique in sedimentary studies. Visual description and classification of particle rounding was used in pioneering studies (eg. Mackie, 1897; Dunn, 1911) and is still used in modern studies (eg. Sneed and Folk, 1958; Bluck, 1969).

Determination of fragment roundness by visual comparison with a set of standards is attractive because of its simplicity, but possesses very insidious disadvantages because it is so deceptively simple (Griffiths, 1967, p.112). These disadvantages are (after Griffith's, 1967) that it is a psychophysical procedure of subjective assessment and almost always suffers from personal prejudice so different observers achieve different results. Furthermore the results for one observer vary from time to time. Nevertheless, visual classification of roundness is frequently used in sedimentary studies and several charts have been devised, presenting images against which clastic fragments may be visually compared (eg. Russel and Taylor, 1937, p.239; Krumbein, 1941; Krumbein and Sloss, 1963, p.111; Powers, 1953, p.118; Pettijohn, 1957, p.59).

Such charts assist the observer towards a more accurate categorising of particle roundness, but were designed primarily for use with sand-sized particles (diameter 0.05mm to 2.0mm) and pebbles (diameter 2mm-64mm), the smaller of the coarse grained clastics, which have been subjected to marine or fluvial attrition, or possibly aeolian weathering or fluvio-glacial transport. The present study is concerned with granite fragments of boulder size (larger than 256mm) that have been subjected to a minimum of glacial and/or periglacial transport, but to a period of subaerial weathering, with only a minor amount of corner and edge rounding.

Wadell (1932) suggested that the images of large objects such as boulders and cobbles must be reduced, and the images of small objects magnified. A standard image size of 70mm was proposed. This technique was not suitable for use with the boulders considered in the present study, which were too large to be carried to the laboratory.

The most appropriate technique for classifying boulder-sized fragments in the field is the five category system of angular, subangular, subrounded, rounded and well-rounded. Useful working definitions of each category were given by Russel and Taylor (1937) in their study of Mississippi River Sands:

Angular	-	edges and corners are sharp.
Subangular	-	fragments still have their original form and faces practically untouched, but the edges and corners are rounded off to some extent, although the angles between the faces may still be sharp.
Subrounded	-	edges and corners rounded off to smooth curves and the area of the original faces is considerably reduced. The original shape of the fragments is still distinct.
Rounded	-	original faces almost completely destroyed, but some completely flat surfaces may be present. There may be broad re-entrant angles between remnant faces. All edges and corners have been smoothed off to broad curves.
Well-rounded	-	No original faces, edges or corners left. The entire surface consists of broad curves. Flat areas are absent. The original shape of the fragment may be suggested by its present form however.

These definitions were used in the present study. Because the fragments studied had nearly planar faces and did not assume the highly angular forms commonly observed in clastic quartz grains, the very angular category suggested by Powers (1953) was not included.

Field Methods

Boulders were sampled in the field using the quadrat method outlined above. Each sample was assessed upon the proportion of edge rounding which was estimated to have occurred, and the extent to which these new facets had encroached upon the original faces of the boulders, according to the definitions.

Difficulties in the field largely centred around the non-rectilinear forms of many of the granite boulders. Where very oblique angles separated faces it was often difficult to judge the effects of weathering as such edges were generally found to be irregular and ill defined, even on freshly derived boulders in rockfall debris. Conversely, where an extremely acute angle separated faces the blocks would still appear to be angular even if all other edges and corners were much reduced. The technique would have been easier to apply if the boulders had been more rectilinear. Nevertheless in the majority of cases 'weathered' and rounded edge and corner surfaces were distinct and their extent could be relatively easily determined.

One hundred boulders were examined from each of the thirteen sampling areas. It was anticipated that a count of this size would tend to even out any discrepancies encountered during the field classification procedure.

Results

Figure 9.2 presents histograms of the results, which can also be conveniently expressed as ratios: the ratios are arranged in order, angular, subangular, subrounded, rounded, well-rounded.

Stuic Corrie

'Inside' 1. 0 - 93 - 7 - 0 - 0 'Outside' 7. 0 - 50 - 45 - 5 - 0

'Inside' 2. 0 - 88 - 12 - 0 - 0 'Outside' 6. 0 - 70 - 30 - 0 - 0

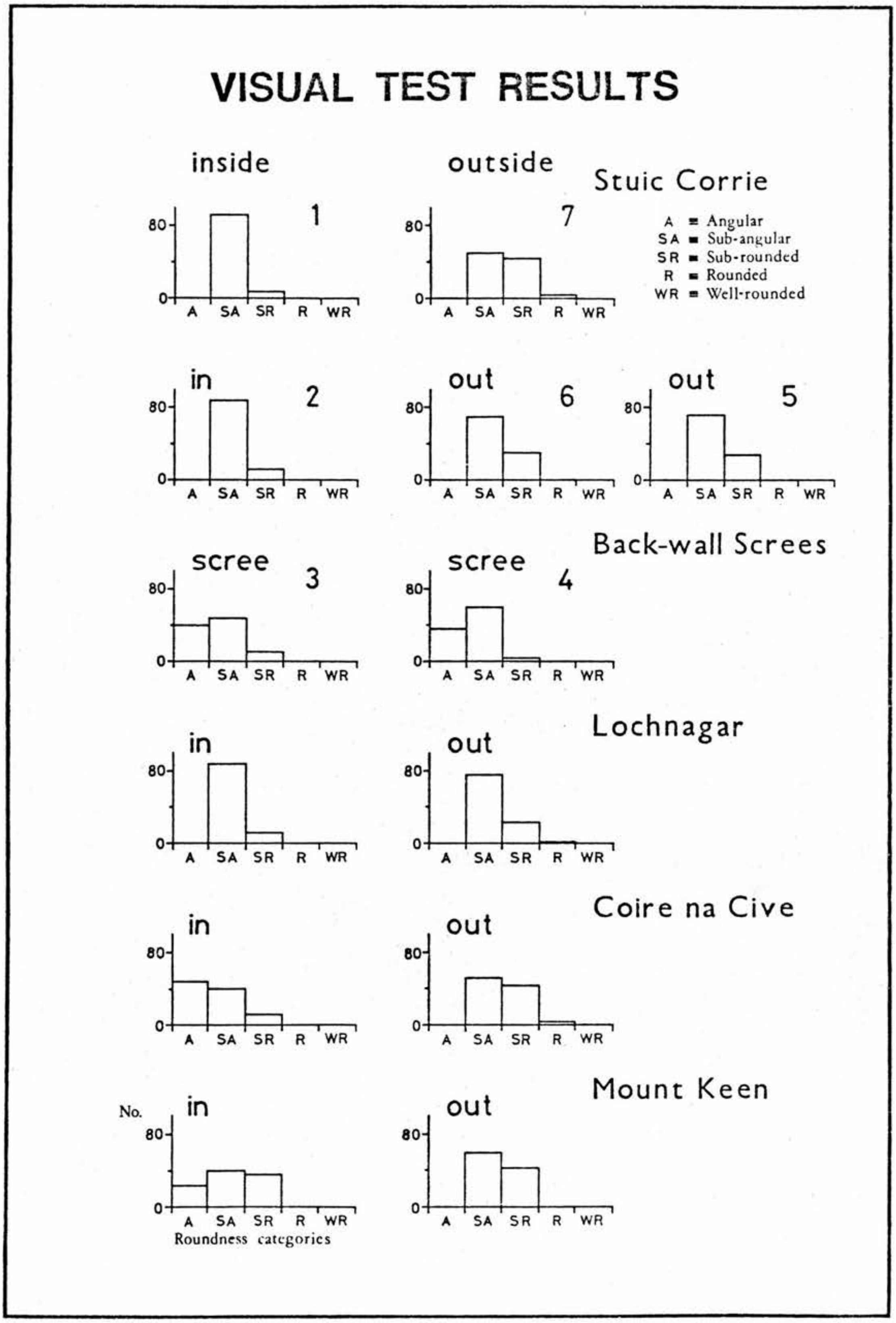

VISUAL TEST RESULTS
inside
outside
Stuic Corrie
1
7
A = Angular
SA = Sub-angular
SR = Sub-rounded
R = Rounded
WR = Well-rounded
in
2
out
6
out
5
Back-wall Screes
scree
3
scree
4
Lochnagar
in
out
Coire na Cive
in
out
Mount Keen
No.
in
out
80
0
A SA SR R WR
Roundness categories

Figure 9.2

Scree 3.	40 - 49 - 11 - 0 - 0	'Outside' 5.	0 - 72 - 28 - 0 - 0
Scree 4.	37 - 60 - 3 - 0 - 0		
Lochnagar Corrie			
'Inside'	0 - 90 - 10 - 0 - 0	'Outside'	0 - 76 - 22 - 2 - 0
Coire na Cive			
'Inside'	47 - 41 - 12 - 0 - 0	'Outside'	0 - 52 - 44 - 4 - 0
Mount Keen Corrie			
'Inside'	22 - 41 - 37 - 0 - 0	'Outside'	0 - 58 - 42 - 0 - 0

Overall the results are largely confined to two categories, namely the subangular and subrounded classes. In some situations the angular class is well represented. No occurrences were recorded in the well-rounded class, and very few were recorded in the rounded class, these all being in 'outside' samples.

The majority of boulders sampled occur in the subangular category. Within all samples, except the Coire na Cive 'inside' situation, the subangular category has the highest percentage representation. Between each pair the occurrences in the sub-rounded class show an increase in the 'outside' ratio from the 'inside' ratio, but within each ratio the percentage in the sub-angular class is always larger.

Only four sampling situations have occurrences in the angular category. The angular class is well represented in the two scree samples and in the Mount Keen and Coire na Cive 'inside' samples. These two corries are alone among the non-scree samples in having occurrences in the angular category.

Discussion of the Results

It appears from the results described above that between each pair of samples, the boulders show a tendency towards increased roundness from 'inside' situations to 'outside' situations. In each 'outside' group the representation in the sub-rounded category increases from the 'inside' reading by from 5 in 100 (Mount Keen example) to 38 in 100 (Stuic 'inside' 1. to Stuic 'Outside' 7.).

The Cive and Mount Keen corries contain large numbers in the angular category, but no angular boulders were sampled from 'outside' either of these two corries, or from the 'inside' or 'outside' of any of the other corries. These results suggest that some process operates in the Cive and Mount Keen corries to supply or maintain angular boulders upon their floor, but that similar processes do not operate upon the floor of any of the other corries, or 'outside' any of the moraines.

Very few occurrences of rounded boulders were recorded and no occurrences of well-rounded boulders. This indicates that the extent to which weathering processes have affected the large boulders of this area has been minimal. Rounded boulders only occur in 'outside' samples, suggesting that weathering processes 'outside' the moraines have had greater effect or have been operating for a longer period.

Taken together these observations demonstrate that the visual tests of determining boulder roundness have detected an increase in roundness from 'inside' to 'outside' situations, but that the magnitude of these differences in terms of affecting the curvature of the corners and edges of the large, angular granite blocks, is slight. Hence the distinction between 'outside' and 'inside' situations is largely made upon the differing relative frequencies within the sub-angular and sub-rounded categories.

The results were expressed as cumulative frequencies and each pair was compared using the non-parametric Kolmogorov-Smirnov two-sample test, which is a method of assessing whether two cumulative frequency distributions come from the same population (or from populations with the same distribution). If two samples are drawn from the same population distribution, it is to be expected that the cumulative distributions of both samples would be fairly close to each other, showing only random deviations from the population distribution. The test focuses upon the largest of the observed deviations between the two groups (Siegel, 1956, pp.127-136).

For samples with 100 variates in each, if the maximum difference in any one step on two superimposed graphs exceeds 23.1% then the two populations can be considered different at the level of significance of 0.01 (99%), and if the value exceeds 19.2% then they are different at the level of significance of 0.05 (95%).

Initially the two Stuic corrie 'inside' results were combined and the three Stuic 'outside' results combined. The resulting pair was found to be significantly different at the 99.9% probability level.

Statistical comparisons between the two Stuic 'inside' distributions with each in turn of the three Stuic 'outside' results were also made:

Stuic Corrie

'Inside 1. 97.5% 'Outside'5.	'Inside' 1. 97.5% 'Outside' 6.	'Inside' 1. 99.9% 'Outside' 7.
'Inside' 2. N.S. (at 0.1) 'Outside'5.	'Inside' 2. 90% 'Outside' 6.	'Inside' 2. 99.9% 'Outside' 7.

Thus each of the pairs are statistically distinguishable at the 97.5% level, except for the Stuic 'Inside' 2. sample with both the 'Outside' 5. and the 'Outside' 6. samples. The latter is distinct at the 90% level. Sample Stuic 'Inside' 2. was collected from boulders lying 'outside' the main floor of the corrie, towards Sandy Loch (Fig 9.1), and sample Stuic 'Outside' 5. from the summit col. Sample Stuic 'Outside' 6., from the flanks of Meall an Tionail, is also less distinct from either of the two Stuic 'Inside' samples than is sample 'Outside' 7., the most 'weathered' (rounded) of the three Stuic 'Outside' samples. The Stuic sample 2., from farther out of the corrie, shows slightly less weathering than sample 'Inside' 1. from nearer the centre of the corrie proper. This slight difference can be seen in the comparisoms above.

The possibility arises that sample 'inside' 2. could contain smaller boulders than sample 'inside' 1., and that sample 'outside' 7. could contain smaller boulders than samples 'outside' 5 and 6. Because of the nature of the technique, for the same amount of subaerial weathering, a smaller boulder would be expected to appear more rounded than a larger one.

To test the possibility that a difference in the average size of boulders from different areas caused the observed differences in roundness, the length (a-axis) of the first 25 boulders of each 100 sampled was measured, and the average length for each site calculated.

Stuic	'Inside' 1 163.0 cm	'Outside' 7 79.0 cm
Corrie	'Inside' 2 157.4 cm	'Outside' 6 68.9 cm
		'Outside' 5 84.9 cm

A slightly lower average boulder size for the Stuic 'inside' 2 sample might explain the marginally more 'weathered' result obtained. Such a possibility is not true for the 'outside' samples. The most 'weathered' sample, sample 7, has a larger average boulder size than sample 6, which is considerably less rounded than 7. Nevertheless, sample 5, the least rounded of the three samples, contains on average, the largest boulders.

What does appear from these calculations is the larger average size of the boulders from samples collected 'inside' the Stuic moraine, than those in the 'outside' samples. In the case of this moraine, the observed differences in the weathering ratios could be a result of the large average size of boulders 'inside' the moraines.

Further consideration of this problem is left until the results from the other three corries have been examined.

The 'inside' and 'outside' pairs for the three other corries were compared using the Kolmogorov-Smirnov two-sample test.

Lochnagar Corrie		Cive Corrie		Mount Keen Corrie	
In	N.S.	In	99.9%	In	97.5%
Out		Out		Out	

The sample pairs from the Lochnagar corrie are not statistically distinguishable at the 90% probability level. This pair shows very similar distributions to the Stuic Corrie 'inside' 2 and 'outside' 5 pair.

Sample pairs from the Cive and Mount Keen corries on the other hand show a highly significant statistical difference. The two samples from the 'inside' situation contain many angular boulders. This might suggest that these two 'inside' samples contain considerably larger boulders than their 'outside' situations, or larger than the boulders from 'inside' the other corries. Once again the length of the first 25 sampled boulders from each situation was measured and the average lengths calculated.

Lochnagar Corrie		Cive Corrie		Mount Keen Corrie	
In	141.0 cm	In	128.0 cm	In	69.4 cm
Out	92.2 cm	Out	104.9 cm	Out	70.2 cm

The high representation of angular boulders in the Mount Keen and Cive Corries does not appear to result directly from a high representation of large boulders. Boulders 'inside' the Mount Keen and Cive moraines are, on average, smaller than those 'inside' the Lochnagar moraine, which does not contain any angular boulders in the sample. The statistically significant difference in roundness between the 'outsides' and 'insides' of the Cive and Mount Keen moraines are not explicable upon the basis of size alone, as the average boulder sizes of the two samples within each pair are very similar.

If size alone were a controlling factor in explaining variations in the observed roundness distributions of the samples, the Lochnagar 'outside' samples should show a ratio more indicative of a greater degree of weathering than it does, as the Cive 'outside' sample more 'weathered', but contains larger boulders on average.

Similarly the average length of the sampled boulders from the 'insides' of the Mount Keen and Cive Corries are smaller the the average lengths of the boulders from both samples within the Stuic corrie. The greater angularity of the boulders 'inside' the Mount Keen and Cive corries is therefore not a direct result of their having a larger average size than boulders within the other corries and hence a smaller proportion of edge and corner rounding to size.

Boulders 'outside' the Cive moraine are, on average, larger than boulders in the three samples gathered from 'outside' the Stuic moraine, but the roundness ratio of the Cive moraine is similar to the roundness ratio of sample Stuic 'outside' 7., the most rounded of the Stuic samples. Samples Stuic 'outside' 7., and Cive 'outside' cannot be distinguished statistically at the 90% probability level (Kolmogorov-Smirnov two- sample test).

The apparent lack of any direct correlation between the average size of boulders contained in the samples, and the weathering ratios of the samples suggests that the observed differences in roundness between 'inside' and 'outside' samples is due to factors other than the size of the boulder.

The two scree samples from the back wall of the Stuic corrie are considerably more angular than the samples from the floor of the Stuic corrie. Samples from the two screes are statistically distinct from each of the samples from the Stuic 'inside' situation (Stuic 'inside' 1 and 2). All four comparisons revealed a difference at the 99.9% level.

The average length of the boulders in each of the two scree samples, calculated from the lengths of the first 25 boulders in each sample, is 86.56 cm (Scree 3) and 66.52 cm (Scree 4) respectively. They are about half the average size of boulders from the two Stuic 'inside' samples, but are significantly more angular. A small proportion of sub-rounded boulders appear in the scree weathering ratios. It is anticipated that these boulders will have been 'weathered' whilst still on the free-face above the scree. Weathering in an exposed situation could account for their relatively advanced state of rounding. Detached fragments, weathering on all sides, could be contributed to the scree from the free face during periods when snow was banked up below. A few 'weathered' (sub-rounded) fragments could thus be contributed intact to the scree.

Samples within the Mount Keen and Cive corries show a high proportion of angular boulders. The Cive sample has a higher representation (47%) in the angular category than the Mount Keen sample (22%).

The two 'inside' samples were statistically compared with the two scree sample distributions from the Stuic corrie to examine the possibility that these two 'inside' samples might have similar population distributions to those of currently active screes.

Mount Keen 'Inside' Stuic Scree 3	99.5%	Mount Keen 'Inside' Stuic Scree 4	99.9%
Cive 'Inside' Stuic Scree 3	N.S.	Cive'Inside' Stuic Scree 4	N.S.

These results suggest that the Mount Keen 'inside' sample does not resemble a scree population, but the Cive'Inside' does have a similar distribution to that of a scree.

Both the Mount Keen and Cive corries are considerably smaller than the Lochnagar and Stuic corries. The Cive corrie is about 0.5 Km across and the Mount Keen corrie about 0.7 Km across compared to 1.5 Km for the Stuic and 1.0 Km for the Lochnagar corrie. The smaller size of these corries, ie. the proximity of the sample sites to the back walls, increases the possibility of rockfalls and avalanches contributing angular boulders to the corrie floors. This possibility is increased in the Cive corrie because of both its small size, and also because of the steeply shelving, chute-like, nature of its back wall (Photograph 8.9). Further, the general lack of surface boulders away from the back of the corrie caused most of the sampling to be concentrated nearer to the back wall than was desirable, and nearer than samples in any of the other corries. Samples within the Mount Keen moraine were also collected partly from the back of the corrie floor as surface boulders were less abundant farther out nearer the moraine.

Finally, statistical comparisons were made between the duplicated Stuic corrie 'inside', and 'outside' situations.

Stuic Corrie

'Inside' 1	N.S	'Outside' 5	N.S.	'Outside' 5	97.5%	'Outside' 6	95%
'Inside' 2		'Outside' 6		'Outside' 7		'Outside' 7	

The two Stuic 'inside' samples are not distinguishable statistically (Kolmogorov-Smirnov two-sample test) one from the other, nor are the Stuic 'outside' samples 5 and 6. Stuic samples 'outside' 5 and 7, and 6 and 7, are statistically distinct at the 97.5% and 95% confidence level respectively,

When the actual roundness ratios are examined it is clear that sample 'outside' 7 is considerably more rounded than sample 'outside' 5, and more rounded, but less extremely so, than sample 'outside' 6. It is thus sample 'outside' 7 which is the 'odd' sample, but this differs from samples 'outside' 5 and 6 in the direction of increased roundness, possibly due to the exposure of the sampling area, upon the south-eastern end of Eagle Ridge.

Summary and Conclusions

The results of the stone rounding tests have been expressed as roundness ratios. Each ratio shows a tendency for the majority of readings to be concentrated in the sub-angular and sub-rounded categories. In all 'outside' ratios there is a distinct increase in the representation within the sub-rounded category from the 'inside' sample, and a corresponding decrease in the representation within the sub-angular category.

This difference points to the direction of the change from 'inside' to 'outside' samples, towards an increased roundness in 'outside' situations. The ratios also highlight the narrow range of difference.

It has been shown that the results are not a direct reflection of difference in the average size of boulders from the 'inside' and 'outside' situations. The greater apparent roundness of the 'outside' samples must be due to some other factor, which it is suggested is a difference in the degree of weathering, whether this be a result of differences in exposure or the length of time the boulders have been subjected to subaerial weathering processes.

The technique used in this study lacked the necessary sensitivity to distinguish a range of weathering states. What the technique did achieve was to point to the small extent to which the post-glacial subaerial weathering has affected the corners and edges of granite boulders in the south-east Grampian study area.

A more refined technique was considered necessary, one which has the ability to differentiate divisions within the sub-angular and sub-rounded categories. The actual amount of rounding accomplished, in terms of the radius of curvature of the 'weathered' edges seemed to offer the best solution. Such an approach is independent of the dimensions of the boulders in the sample; hence fewer problems would be presented when comparing the roundness of different populations. It would also serve to expand the narrow range of groupings distinguished by the present technique to allow a more detailed analysis and discussion.

The refined procedure is described in the succeeding section.

9.1b Template Studies

Introduction

The previous technique relied upon the ability of the observer to assess the amount of edge rounding of each block in relation to its size. It became apparent that the overall roundness of the blocks did not provide sufficiently detailed information about the amount of weathering that each block had undergone. What is of more relevance is the actual radius of curvature that has been developed. By this it is meant that a boulder 3m long could have its edges 'weathered' from angular to curved edge surfaces of 20 cm radius but still be classified as subangular, whereas a block of only 0.5m diameter with similarly curved edges would appear well rounded. It was this problem that stimulated the search for methods of measuring the amount of edge rounding.

A form of variable stencil or template that could rapidly adjust to the form of the 'weathered' edge and corner surfaces seemed to offer the best solution. The Copydex "Mimic" Instant Shape Tracer was selected as being the most suitable for use in the field. This instrument consists of a steel spring clamp, 15cm long, which holds about 165 fine steel rods of approximately 0.5 mm diameter. The rods are held closely together side by side as a 15cm long row, like the teeth of a comb. The spring clamp allows the rods to move slowly through it when pressure is applied to either of the ends of the rods. Thus, when one edge of the row of rods is pressed against a shaped surface, the individual rods move differentially against each other until each end is in contact with the surface. When the shape tracer is removed from its contact with the profiled surface, the spring clamp ensures that the rods are not allowed to move. Any complex profile up to 15 cm long can be reproduced. The length of the rods allows for a relief amplitude of up to 4.25 cm, and minor relief irregularities down to 0.5 mm wide (the diameter of the rods) are faithfully reproduced. Two profiles are produced. The contact profile represents the external form of the surface followed, and the other ends of the rods trace out a curve representing the internal form of the same curve.

A series of radius curves were constructed against which the profiles could be checked. These curves ranged from 1 cm to 20 cm diameter, at 1 cm intervals.

Previous work

Rigid radius curves, in various forms, have long been used in sedimentary studies for measuring the radius of curvature of the rounded edges of sand to cobble sized particles. Few uses of flexible templates have been reported, and few studies have examined the rounding of boulder sized fragments.

Wentworth (1919) conceived the important idea of measuring the radius of curvature of the sharpest developed corner of cobble sized fragments during a study designed to establish a method of asessing the roundness of sedimentary particles. He used a rigid gauge, consisting of 14 curves ranging from 1-14 mm radius. Later, Cailleux (1945, 1947) devised a 'roundness target' for measuring the radius of selected edges upon pebbles and later sand sized particles. The target is held behind the measured fragment and the desired edge sighted against each radius curve shown until the best fit curve is selected. Keunen (1956) utilised a similar rigid gauge showing curves of 1/5 or 1/10 mm intervals for the microscopic examination of sand grains. A further refinement of this principle was made by Dobkins and Folk (1970). They used modified 'Wentworth Circles' inscribed upon a transparent plastic sheet. This method allowed the template to be used as a sighting target for measuring the radius of curvature of a circumscribed circle, or as a lay-on template for measuring inscribed circles.

Similar templates, often known as the 'Cailleux Roundness Target', have been used in many subsequent studies of sedimentary particles, in the 4mm-120mm fraction, from arctic environments (eg. King, 1969; King and Buckley, 1968; McCann and Owens, 1969; Dugdale, 1972).

Wentworth (1922) developed a variable template from an opticians test indicator which he used successfully in a study of pebble rounding. The modified instrument was capable of measuring changes in the range of curvature of a surface down to 0.03 mm. The rigid templates, conceived by Wentworth (1919), have gained favour over the variable form, and are now used exclusively.

Field Methods

The field sampling procedure employed the quadrat method used in the visual assessment of roundness, and at the same sampling areas.

Fifty boulders were examined in each quadrat, and four readings were made at every boulder, thus each sample comprises 200 readings.

The uppermost four edges of each boulder located by the quadrat were measured. Measurement involved placing the template former tangentially against the weathering edge surface, at a point midway along the edge. In each case it was necessary to ensure that the straight edge of the re-set template former was placed as nearly as possible at right angles to the bisector of the angle between the two faces whose contact edge was being measured. This precaution allowed the most accurate profile to be produced, when the ends of the rods meet the edge surface as vertically as possible rather than obliquely.

Four edges were measured so that a representative selection could be presented for each boulder. Sampling four edges presented fewer problems regarding the choice of which edge or pair of edges to select for profiling. In practice, four edges were usually present bounding an upper, nearly horizontal, boulder face. If only three edges, or less, were uppermost, readings were taken from vertical edges. The sampled vertical edges were selected in an order depending upon which terminated at the highest point above the ground.

From a weathering point of view upper edges were considered to be the most representative indicators of the effects of subaerial weathering above any influences of peat, vegetation and associated acidulated ground waters. In most cases the boulders stood in a peaty accumulation of varying depth from either a thin A_o horizon to a thick blanket peat.

The profiling process consisted of pressing the template former squarely against the edge surface until the rods had contacted the complete profile of the surface and the outer rods began contacting the boulder faces. A concave contact profile is produced, which merges into straighter profiles. The convex profile produced at the other end of the rods is then tried for best fit against an ascending series of centimetre radius curves drawn upon a field chart. Profiles are then assigned a value that represents the radius of curvature. In the case of a profile falling between two radius curves, the lower radius was selected as the representative one.

Difficulties encountered in the field were few, and, as in the visual classification technique, were largely a result of the irregular nature of the boulders. In some cases it was difficult to select four upper edges, as in the case, for instance, of a boulder emerging from the ground in the form of the upper portion of a tetrahedron. This was never found to be a prohibitive difficulty, as edges were not usually continuous for any distance, undergoing changes in direction or bifurcation and so the new facets were treated as separate edges. Following from this problem, the lack of continuous edges often made the determination of the mid-point of any edge an arbitrary decision.

Results.

The field chart was constructed to show a series of radius curves from 0 to 20 centimetres. In practice it was found that, among the thirteen samples, no edge surface exceeded 13 cm radius. The results are presented as histograms (Fig 9.3) showing the data in 1 cm radius classes from 0 to 13 cm.

It is immediately apparent that the histograms show nearly normal distributions with a tendency to be positively skewed, the larger radius values providing a tail to the distributions. Closer inspection reveals that the modal values or peak of the distributions tend to be moved further to the right, towards the higher radius categories, from the 'inside' samples to the 'outside' samples.

In all the 'Inside' cases the histograms show a modal value of 4 cm radius. The Stuic 'inside' 2 and the Mount Keen 'inside' samples have additional modal peaks of 3 and 2 respectively. All the 'outside' results have a modal value of 5 or 6.

A similar situation is reflected in the values of the mean and median radius for each sample. The 'inside' samples have mean values of from 2.71 cm (Cive) to 4.21 cm (Stuic 'inside' 1). 'Outside' sites have means ranging from 4.55 cm (Mount Keen) to 6.0 cm (Lochnagar). Similarly, 'inside' sites have median values ranging from 2.18 cm (Cive) to 3.28 cm (Stuic 'inside') and 'outside' sites from 3.98 cm (Mount Keen) to 6.00 cm (Stuic 'outside'6).

Both 'inside' and 'outside' samples have small standard deviations ranging from 1.45 (Lochnagar 'inside') to 2.37 (Cive ('outside').

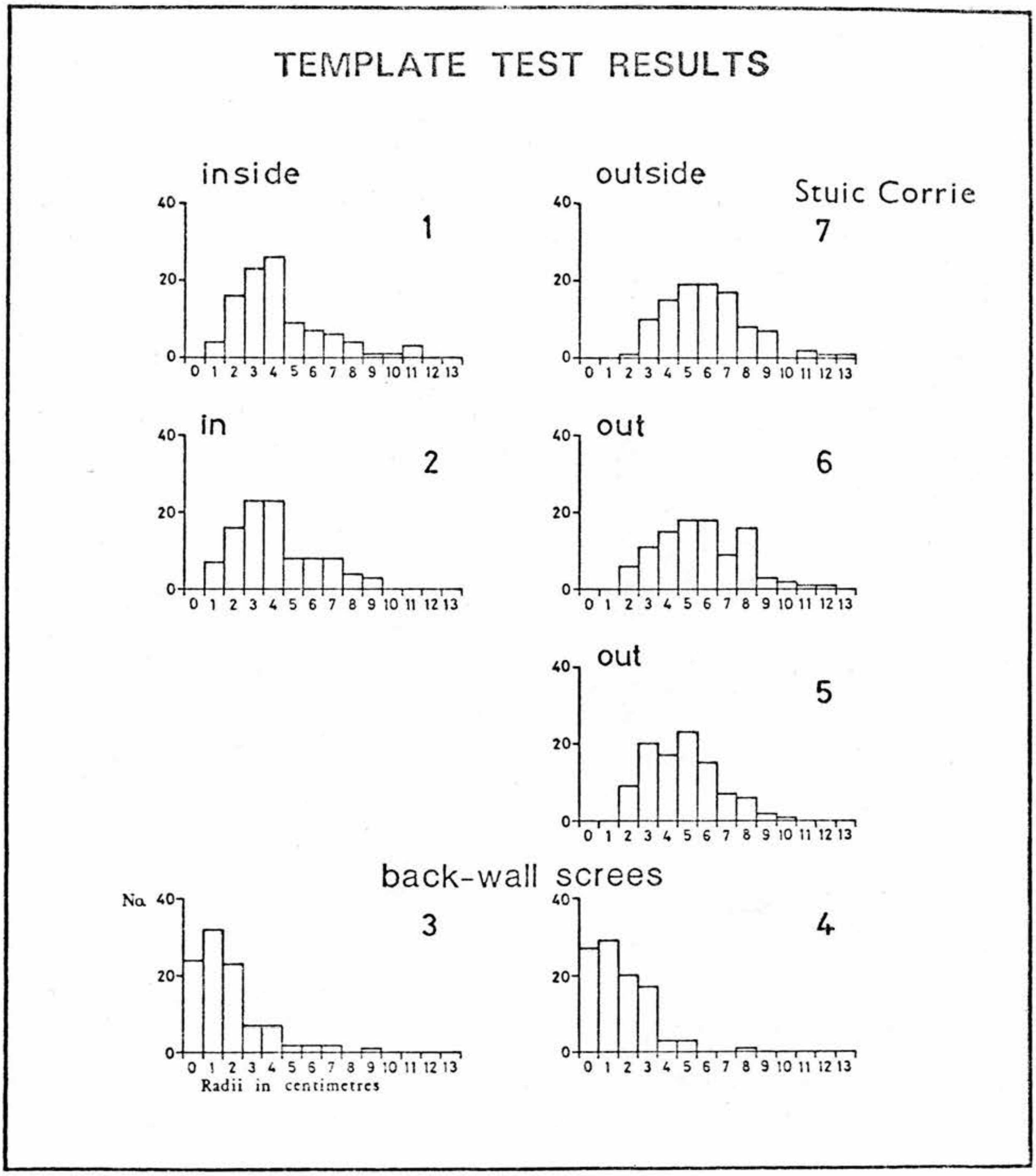

TEMPLATE TEST RESULTS
inside
outside
Stuic Corrie
1
7
in
2
out
6
out
5
back-wall screes
3
4
No.
Radii in centimetres

Figure 9.3a

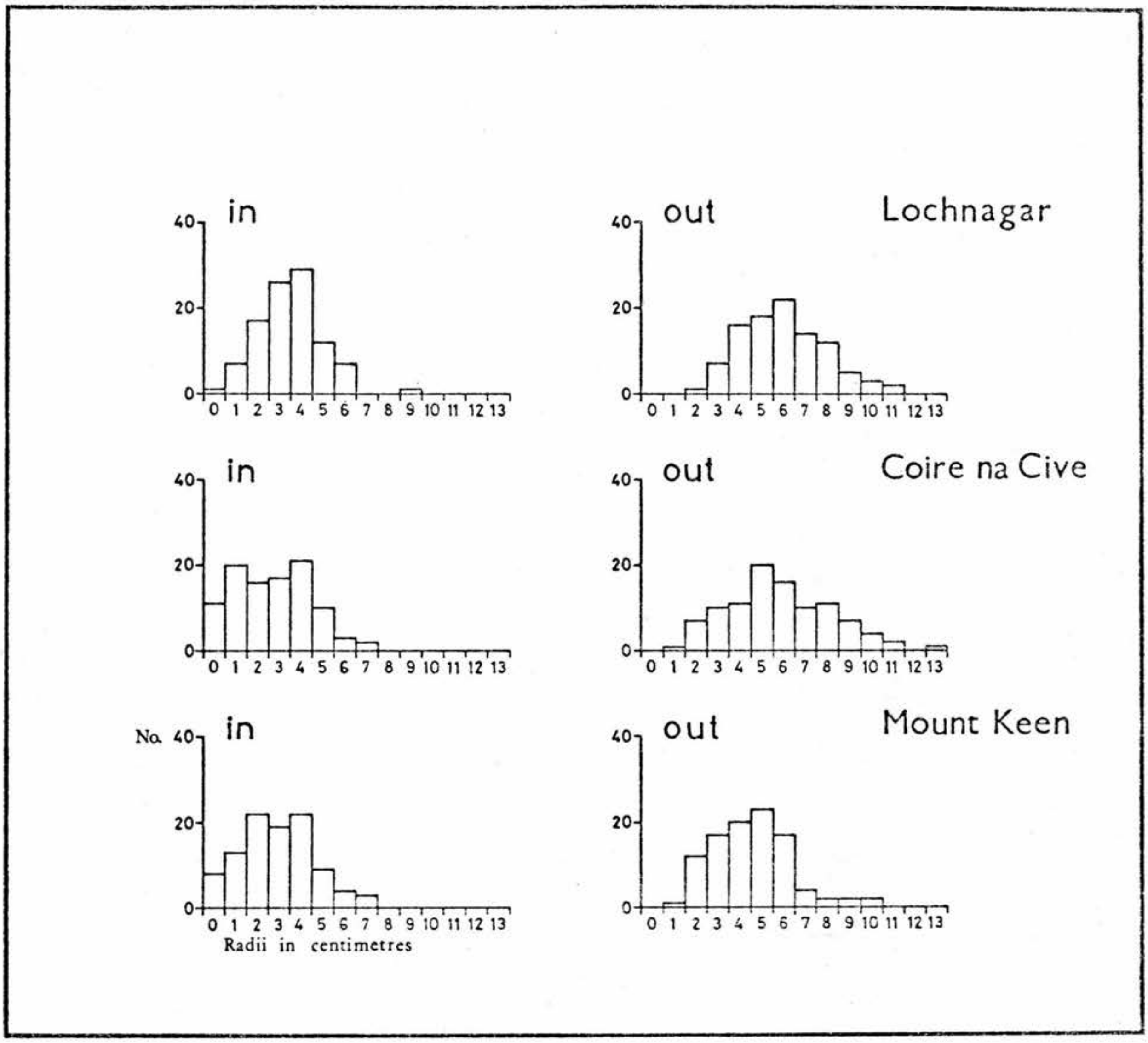

in
out
Lochnagar
in
out
Coire na Cive
No.
in
out
Mount Keen
Radii in centimetres

Figure 9.3b

The scree samples have modal values of 1, and have mean values of 1.74 (Scree 3) and 1.56 (Scree 4) respectively. Median values are 0.82 and 0.81 respectively.

Details of the distributions are given below:

Stuic Corrie	mode	mean	median	standard deviation	range
'Inside' 1	4	4.21	3.28	2.14	1-11
'Inside' 2	3+4	4.02	3.17	1.997	1-9
Scree 3	1	1.74	0.82	1.771	0-9
Scree 4	1	1.56	0.81	1.395	0-8
'Outside' 5	5	4.75	4.16	1.799	2-10
'Outside' 6	5+6	5.64	6.0	2.119	2-12
'Outside' 7	5+6	5.95	5.28	2.068	2-13
Lochnagar					
'Inside'	4	3.45	2.96	1.445	0-9
'Outside'	6	6.00	5.37	1.921	2-11
Cive					
'Inside'	4	2.71	2.18	1.738	0-7
'Outside'	5	5.805	5.06	2.365	1-13
Mount Keen					
'Inside'	2+4	2.91	2.36	1.698	0-7
'Outside'	5	4.55	3.98	1.802	1-10

From the histograms (Fig. 9.2) it can be seen that all of the 'inside' samples show a rapid decline in the frequencies in categories above 4 cm radius. This difference ranges from between 23 in 200 (Cive) to 35 in 200 (Stuic 'inside' 1).

The greater proportion of the results occurs below 5 cm (0-4) for the 'inside' samples; conversely the greater proportion of the results in the 'outside' samples are of 5 cm and above. The percentage below 5 cm radius in each sample are shown below:

Stuic

'Inside' 1 69% 'Outside' 7 25.5%

'Inside' 2	69%		'Outside' 6	32%
			'Outside' 5	46.5%
Scree 3	93%			
Scree 4	96%			
Lochnagar				
'Inside'	80%		'Outside'	24%
Cive				
'Inside'	85%		'Outside'	29%
Mount Keen				
'Inside'	84%		'Outside'	50.5%

These results indicate the greater degree of rounding of the 'outside' samples than the 'inside' samples.

The cumulative distributions for the 'inside' and 'outside' sample pairs were compared using the Kolmogorov-Smirnov two-sample test. The results of the tests showed each pair to be significantly different at the 99.9% confidence level. Both Stuic corrie 'inside' samples were compared with each of the three 'Stuic 'outside' samples and shown to be different at the 99.9% confidence level.

Comparisons between the Stuic samples for similar situations revealed the following results:

Stuic Corrie

'Inside' 1	N.S				
'Inside' 2					
'Outside' 5	95%	'Outside' 5	99.9%	'Outside' 6	N.S
'Outside' 6		'Outside' 7		'Outside' 7	

These results indicate that samples 'outside' 6 and 7 are similar in their population distributions, whereas 'outside' 5 and 7 are very significantly different. Examination of the histograms and the percentage of readings occurring below 5 cm radius in each sample demonstrates that sample Stuic 'outside' 7 is the most rounded of the three Stuic 'outside' samples, and sample 5 is the least rounded.

There is no statistical difference between the two Stuic 'inside' sample populations with this technique.

The two Stuic scree samples differ from each of the two Stuic 'inside' samples at the 99.9% confidence level. A statistical comparison between the two scree samples shows that there is no statistically significant difference between the two sample populations.

It is apparent from the histograms that the Lochnagar, Cive and Mount Keen corrie 'inside' samples are more angular than the two Stuic 'inside' samples. The Cive corrie has a high proportion of 0 cm and 1 cm values (30.5%). The proportions are less in the Mount Keen (21.5%) and Lochnagar corries (8.5%). Very few edges were as angular as 0 cm and 1 cm in the Stuic samples 'inside' 1 (4%) and 2 (7.5%), there being no 0 cm occurrences as are seen in the other three corries.

The Mount Keen and Cive corrie sample populations were compared with each of the two Stuic corrie scree samples to test the possibility that these two most angular 'inside' samples might have population distributions similar to screes. It was shown that the two 'inside' samples differed from each of the two scree samples at the 99.9% confidence level.

Of the 'outside' samples the Mount Keen sample is the most angular, and the Lochnagar sample the least angular, having a very similar population distribution to the Stuic 'outside' 7 sample.

Discussion of the Results

The results of the template studies show a slight, but distinct tendency for increasing boulder roundness from 'inside' to 'outside' moraine situations. There is a variation apparent between the results for similar situations between different moraines, but within each pair the 'outside' sample is always more rounded than the 'inside' sample. Thus, for instance, although the Mount Keen 'inside' sample is the most angular of the 'inside' samples, and the Mount Keen 'outside' sample is the most angular of the 'outside' samples, the magnitude of the difference between the two samples is similar to the difference between the other moraine pairs.

These results indicate that there are areal variations in the roundness values obtained from different 'inside' sites, or from different 'outside' sites. Nevertheless the sampled populations have certain characteristics in common which serve to act as diagnostic indications of 'inside' or 'outside' sites.

'Inside' sites are characterised by populations of roundness indices with modes of 4, or below 4, a mean of less than 4.25 and a median of less than 3.5. 'Outside' sites are characterised by a modal value of 5 or 6, a mean of more than 4.5, and a median of more than 3.75. Although 'outside' ranges are usually more extensive than 'inside' ranges, the actual range of roundness values recorded for each situation is not usually distinctive. What is distinctive about the population distributions is the proportion of readings of 4 cm radius and below, in the 'inside' sites, and of 5 cm and above in 'outside' sites. 'Inside' sites are characterised by having 69% or more of their readings at 4 cm and below, and 'outside' sites by having less than 51% at 4 cm or below.

The amount of increase in roundness in terms of centimetres radius is small, representing a shift in the mode of only 1 cm, or slightly above. Nevertheless a shift in the mode of only 1 cm is a shift of 10% as the average is only 1.1 cm to 10.2 cm. This small range indicates the small amount of edge weathering the boulders have undergone.

The Cive and Mount Keen corries contain the most angular boulders of all the four corries. This could be explained by a difference in the weathering characteristics of the granite in these two corries. Such an explanation is plausible in the case of the Mount Keen corrie as the 'outside' sample is the most angular of the 'outside' samples. This explanation is hardly tenable for the Cive corrie which occurs between the Stuic and Lochnagar corries, at the end of the ridge separating the two. It is possible that the ridge is a structurally located feature formed by a zone of more resistant granite, consequently the granite debris shed from the end of the ridge into the Cive corrie would be more resistant to weathering hence more angular. What seems more likely is that the Cive corrie, being of such small dimensions, would receive a greater contribution of avalanche and rockfall debris onto the corrie floor and into the sampling zone. This point raises interesting comparisons between the visual technique and the template technique for assessing boulder roundness.

From the results of both tests the Cive 'inside' sample is the most angular of the 'inside' samples followed in order of increasing roundness by the Mount Keen 'inside' sample. The order for the other three 'inside' samples differs between the two techniques, but the Lochnagar and Stuic 'insides' 1 and 2 are rather similar in both teqhniques, bearing more affinity to one another than to the Cive and Mount Keen 'inside' samples.

Between the 'outside' samples, the Mount Keen sample is the most angular in the template tests, and the Lochnagar sample is the most angular in the visual tests. The three Stuic 'outside' samples are similarly different in each test, 'outside' 7 being the most rounded and 'outside' 5 being the least rounded.

Summary and Conclusions

The application of the template roundness tests to the granite boulder samples from standard sampling sites 'inside' and 'outside' the limits of four corrie moraines in the south-east Grampians has provided results sinilar to those from the pilot study which involved a visual assessment of boulder roundness. Boulders 'outside the limits of the corrie moraines are more rounded than boulders from sites 'inside' the moraines. The magnitude of this difference is small, a feature highlighted by the results of the visual tests, but certain features of the sample populations are characteristic of 'ihside' or of 'outside' sites.

Thus 'inside' sites could be expected to provide results with a modal value of 4, or 4 and less, a mean of less than 4.25, and a median of less than 3.5. 'Outside' sites show modal values of 5 or 6, a mean of more than 4.5, and a median of more than 3.75. Although the magnitude of this difference is small, only about 1 or 2 cm, the average range of radii measured was only 1.1 to 10.2 cm, therefore a shift of 1 cm inthe mode represented a shift of 10% of the range.

Variations between 'outside' sites, and between 'inside' sites have been demonstrated, indicating that areal variations in the amount of weathering accomplished do occur: the characteristics of 'outside' populations are similar, but are distinct from those of 'inside' sites which are similar within themselves. It is therefore concluded that 'outside' sites as a whole contain boulders which are rounded to a greater extent than those from 'inside' sites.

The differences shown between samples from 'inside' sites and the differences shown between samples from 'outside' sites can be attributed to the differences between the sites in terms of aspect and exposure, and areal variations in the nature of the granite. Such variations could not explain the distinctiveness of the 'outside' sites from the 'inside' sites, in terms of greater weathering of the former. It is therefore proposed that the boulders 'outside' the limits of the former corrie glaciers show definite evidence that they have been exposed to subaerial weathering for a longer period than those 'inside' the limits ie boulders 'inside' the corrie glacier limits appear to be fresher than those 'outside' the limits.

9.2 Studies of Boulder Disintegration - Granite Weathering Ratios

9.2a Rubbing Tests

Previous Work

Blackwelder (1931) used thirteen age criteria to distinguish between the deposits of different glacier advances in the Sierra Nevada and Basin Ranges of North America. The most useful criterion was the weathering of boulders in till. Because the weathering rates of different rock types were not readily comparable, attention was concentrated upon a single rock type, the average granodiorite of the Sierra Nevada batholith.

Boulders of the Sierra Nevada granodiorite were sampled at various locations, and classified by Blackwelder as

a. almost unweathered

b. notably decayed on the surface but still solid

c. greatly weathered, cavernous or rotten

The resulting figures constituted a ratio known as the 'granite weathering ratio', or G.W.R.. According to Blackwelder, a ratio of 90 - 10 - 0 certainly indicated the most recent age, the Tioga stage, about 25,000 to 10,000 B.P.. A ratio of 30 - 60 - 10 was typical of the Tahoe stage, the penultimate stage of a four fold glacial sequence, and one of 0 - 30 - 70 was representative of the older tills.

Birman (1964) used the ratio of fresh to weathered granite boulders to confirm his correlations of glacial deposits between different canyons, and across the crest of the Sierra Nevada. He identified the deposits of seven glacial advances in three groups on the western and eastern slopes of the Sierra Nevada. Blackwelder (1931) had used the G.W.R to compare granodiorite boulders contained in till, but Birman (1964) examined granite boulders weathering upon the surfaces of moraines. The G.W.R. was considered by Birman to be "the final determinative test of a wide age disparity among the several deposits."

Advantages of the G.W.R. technique are (Birman, 1964):

1. It is a quantitive technique
2. The quantitive results can be compared directly with results from other areas because the characteristic tested is a function primarily of age rather than the process of formation of the deposits.
3. It is simple, and the fast application allows more observations than do other quantitive methods.
4. The results can be statistically analysed.

The variables that might affect the technique were listed by Birman as:

1. Lithological differences. Marked changes in texture and composition result in significant differences in the rate of weathering.
2. Successive uncovering of fresh boulders by washing out of the morainal matrix would give abnormally high ratios of fresh to weathered boulders.
3. Accidental non-random covering of some boulders might influence the ratio.
4. Differences in weathering resulting from different orientations of slope, differences in altitude, rainfall and effects of wind.
5. Presence of boulders weathered before transport.
6. Personal bias of the observer.

Birman did not use Blackwelder's (1931, p.877) three categories, he only distinguished fresh and weathered boulders, defined as follows:

Fresh : if on more than half its exposed surface the weathering did not penetrate to the depth of an average grain diameter. Surfaces smooth.

Weathered : if weathering had penetrated to at least the depth of an average grain diameter. The rock surface was therefore crumbly and a light hammer blow disrupted a loosened assemblage of grains.

Weathered boulders were found incorporated in end moraines rather than recessional moraines, as end moraines represent the clearing out of a former weathered land surface.

Each count consisted of 100 boulders of 0.33 metre diameter or larger. To eliminate bias the results were called out to a recorder so the observer was unable to see how the counts were progressing. On some morainic crests two counts were performed. When the two results were compared they were found in most cases to agree within 5%. Results were also highly consistent using two observers and one recorder.

Reasonable success was achieved using the G.W.R. technique on a glacial reconnaissance in Turkey (Birman, 1968). The scarcity of granite in some of the localities visited made it impossible to attempt correlations between all the moraines examined.

Carrara and Andrews (1972) dated the younger moraines of the Northern Cumberland Peninsular, Baffin Island, by lichenometry and used rates of weathering for dates older than about 6,000 B.P..The two authors employed the method, pioneered by Blackwelder and Birman, of determining the percentage of weathered boulders upon each moraine.

Their distinguishing criteria differed from those previously used because the deposits investigated were relatively young, and weathering rates in the Arctic are slow.

The category criteria were :

Fresh : the boulder surface felt smooth, or at least not gritty.

Weathered : any boulder which when rubbed with the hand resulted in the flaking ~~of a number~~ of a number of grains.

One hundred boulders were sampled from each moraine. No specific sampling stations were set up.

The test was based on the assumption that at the time the moraine was deposited all the rocks within and upon the moraine would have been fresh. With time, all the boulders would have undergone granular disintergration. The method proved useful for separating the younger moraines, but its discriminating power was lost when the percentage of weathered boulders exceeded 80 per cent. Boulders were examined only in those areas which had lichens present, which indicated that the boulders had been exposed to subaerial weathering for some time.

A report of further boulder weathering studies from the Northern Cumberland Peninsular, Baffin Island was prepared by Dugdale (1972). Five weathering classes were established to evaluate the progressive subaerial disintergration of boulders with time.

The classes were :

a. Boulder surface smooth.
b. Boulder surface rough and granular.
c. Granules easily removed with a penknife.
d. Grus surface on a boulder with a solid core.
e. Completely grussified boulder.

All the boulders examined were a granitic granulite. The moraine systems of each glacial phase were found to show characteristic histograms, making it possible to discriminate between the deposits of different ages.

Calkin and Cailleux (1962) used a similar technique to establish a relative chronology for a series of four successive moraines left by the retreating Lower Victoria Glacier, Antarctica. The true ages of the moraines were not known. Their study concentrated upon the extent to which boulders of granite and gneiss contained in the moraines, had undergone cavernous weathering since deposition.The size of the cavities produced, the number of cavities in each boulder and the percentage of boulders affected at each site were related to age. It was found that the incidence of hollows decreased from 86% to 57%, to 28% to 12% upon successively younger moraines.

The Present Study

It has been shown above how workers in several areas successfully developed relative chronologies for successive glacial advances based upon the extent to which boulders, usually of one particular lithology, show progressive signs of surface decay under the influences of subaerial weathering processes. The extent of weathering is determined, regardless of its relative action upon the edges and corners of the boulders. A similar approach was used to classify the weathering states of granite boulders occurring 'inside' and 'outside' the limits of four presumed former corrie glaciers in the South East Grampians.

The present study differed from previous ones in that it attempted to differentiate between boulders situated upon the ground covered by the presumed Loch Lomond Age corrie glaciers, and those upon ground 'outside' and immediately adjacent to these limits. Former studies examined boulders occurring upon the surfaces of several moraines. Not all the corries in the present study area had bounding moraines evident.

For the purposes of the present study, five weathering categories were established. Reconnaissance surveys did not reveal the existence of crumbling and rotten granite boulders, similar to those seen in California (Blackwelder, 1931; Birman, 1964, 1968). Hence the categories selected were similar to those used in the Arctic by Dugdale (1972). By using five subdivisions it was hoped that the technique would be sufficiently delicate to detect small changes in the weathering states of the boulders being sampled. The weathering categories are fairly clearly defined, but as with all classifications of natural phenomena, the boundaries are necessarily artificial, boulders in the field showing angradation from completely fresh to extensively flaking.

The categories are :

1. Boulder surface fresh and clean, the faces of the boulders representing unweathered joint or fracture surfaces.
2. Boulder surface has a rough and granular feel. When the surface is rubbed with the hand a few isolated grains are detached.
3. Boulder feels gritty. Showers of grains fall off from more than half the total surface of the boulder under light finger pressure.
4. Evidence of minor flaking. Showers of grains fall off from over the whole surface, under light finger pressure, and some small flakes or crystal clusters are easily removed by the finger nail.

5. Boulder surface extensively flaking and showing signs of pitting. Areas of the surface can be crumbled by the hand.

The field test involves examining the surface of each boulder, using only the bare hands of the observer, to estimate the extent to which subaerial weathering has penetrated the rock. If weathering has penetrated the surface up to half the average crystal diameter, the rock feels rough and granular (category 2). In a few places on such a boulder, isolated grains may have weathered to the depth of the average crystal diameter so crystals can be detached using only light finger pressure. A further stage is reached when over half the boulder surface is weathered to the depth of an average crystal diameter (category 3). In this case showers of grains fall off from large areas of the boulder surface. As weathering extends deeper, flakes or crystal clusters are loosened from small areas of the surface, the whole of the surface releasing single grains under finger pressure (category 4) More extensive flaking, at which stage large flakes could be prised off and areas of the surface crumbled by the hand (category 5), was the most advanced weathering state examined.

Field Methods

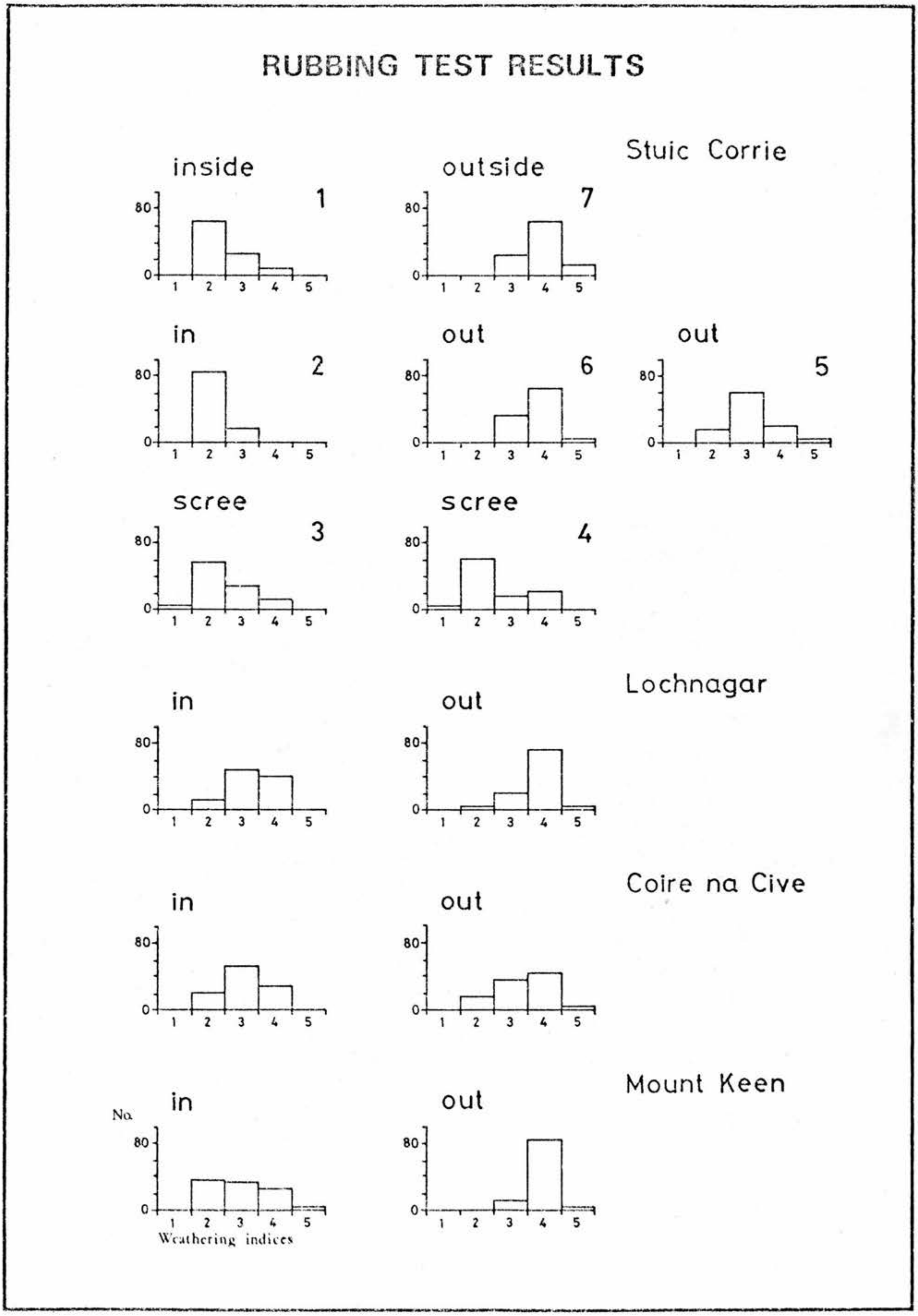
The quadrat sampling method used for the previous two roundness studies was again employed at the same sites.

Each boulder sampled was tested using the bare hands to rub the boulder surface. An estimate was made of the depth to which subaerial weathering had penetrated the surface and the approximate percentage area of the boulder over which this decay had extended. This procedure enabled the boulder to be assigned to a weathering category. Following the method of Birman (1964), one hundred boulders were sampled at each site, the results being called out to a recorder.

Only upper surfaces were examined. The lower surfaces near ground level were avoided in case the moist and acid peat or vegetation layer had caused differential weathering at the base.

Results

The results of the rubbing tests have been expressed as Granite Weathering Ratios 'Blackwelder, 1931); and are also shown in histogram form (Fig 9.4).



RUBBING TEST RESULTS
Stuic Corrie
inside
1
outside
7
in
2
out
6
out
5
scree
3
scree
4
Lochnagar
in
out
Coire na Cive
in
out
Mount Keen
in
out
No.
80
0
1 2 3 4 5
Weathering indices

Figure 9.4

Stuic

'inside' 1	0 - 65 - 27 - 8 - 0	'outside' 7	0 - 0 - 24 - 63 - 13
'inside' 2	0 - 84 - 16 - 0 - 0	'outside' 6	0 - 0 - 31 - 64 - 5
		'outside' 5	0 - 16- 59 - 21 - 4
Scree 3	5 - 55 - 29 - 11 - 0		
Scree 4	4 - 60 - 15 - 21 - 0		

Lochnagar

'Inside'	0 - 12 - 47 - 41 - 0	'outside'	0 - 5- 20 - 71 - 4

Cive

'inside'	0 - 20 - 53 - 27 - 0	'outside'	0 - 15—37 - 44 - 4

Mount Keen

'inside'	0 - 37 - 35 - 25 - 3	'outside'	0 - 0- 12 - 83 - 5

There are few fresh boulders (category 1) and a few well-weathered boulders (category 5) occurring in the ratios, consequently the majority of the results are distributed between categories 2, 3 and 4. Only in the scree sample do any fresh boulders (category 1) occur, and with the exception of the Mount Keen 'inside' sample, well weathered boulders (category 5) only occur in 'outside' sites. Between each pair of results the 'outside' sites show an increased proportion of readings in the higher categories suggesting that 'outside' samples are more weathered on the whole than 'inside' samples. Differences are apparent in the degree of weathering between 'inside' sites, and between 'outside' sites.

'Inside' sites have a modal value of 2 or 3, and 'outside' sites have a modal value of 4, except for the Stuic 'outside' sample 5 which has a modal value of 3.

Weathering category 2 has a mean percentage representation of 43.6% for 'inside' sites and 6.0% for 'outside' sites. Category 3 has a mean percentage representation of 35.6% in 'inside' sites and 30.5% in 'outside' sites. Similar values for category 4 are 20.2% and 57.7% respectively. This relationship suggests that, on average, category 3 is similarly represented in both 'inside' and 'outside' sites, rather less in the latter. The bulk of the 'inside' readings are concentrated in category 2, and the bulk of the 'outside' readings in category 4.

Discussion of the Results

Following the procedure adopted by Dugdale (1972) the percentage of fresh boulders at each site was calculated. Categories 1 and 2 were considered to constitute fresh boulders, and categories 3, 4 and 5 weathered boulders.

Stuic	'inside' 1	65%	'outside' 7	0%
	'inside' 2	85%	'outside' 6	0%
			'outside' 5	16%
Scree 3	60%			
Scree 4	64%			
Lochnagar	'inside'	12%	'outside'	5%
Cive	'inside'	20%	'outside'	15%
Mount Keen	'inside'	37%	'outside'	0%

In all cases there is a higher percentage of fresh boulders in 'inside' sites than 'outside' sites. The difference is most marked in the Stuic and Mount Keen samples, the Lochnagar and Cive samples showing much less of a distinction.

The mean and median reading for each category are shown below.

	mean	median		mean	median
Stuic					
'inside' 1	2.43	1.77	'outside' 7	3.89	3.14
'inside' 2	2.16	1.60	'outside' 6	3.74	3.30
			'outside' 5	3.13	2.58
Scree 3	2.46	1.82			
Scree 4	2.53	1.77			
Lochnagar					
'inside'	3.29	2.81	'outside'	3.74	3.35
Cive					
'inside	3.07	2.57	'outside'	3.37	2.95
Mount Keen	2.94	2.37	'outside'	3.93	3.46

These figures indicate the amount of overlap between the characteristics of the samples. 'Inside' sites have mean values of less than 3.3 and median values of less than 2.9. 'Outside' sites have mean values of more than 3.1, and median values of more than 2.5. Neither the mean weathering index for samples nor the median index is a diagnostic indicator of 'inside' or 'outside' samples.

The two situations can be most markedly contrasted if the ratios are re-grouped to compare the proportion of the results depicting the granular disintegration stage of weathering with those depicting the flaking stage. Thus categories 2 and 3, compared with categories 4 and 5, as a new ratio, provide the most diagnostic ratios (expressed as percentages).

Stuic			
'inside' 1	92/8	'outside' 7	24/76
'inside' 2	100/0	'outside' 6	31/69
		'outside' 5	75/25
Scree 3	89/11		
Scree 4	79/21		
Lochnagar			
'inside'	59/41	'outside'	25/75
Cive			
'inside'	73/27	'outside'	52/48
Mount Keen			
'inside'	72/28	'outside'	12/88

A distinction is now made much more clear. All 'inside' sites, with the exception of the Lochnagar sample have an index of granular weathering of more than 70. When the Lochnagar case is included the lower threshold value is then 59. Among the 'outside' sites the Cive and Stuic 5 samples are exceptional. All the other samples show flaking indices of more than 65. The Stuic 'outside' 5 sample, from the summit col, is less weathered than several of the 'inside' samples, and the Cive 'outside' sample appears much less weathered than the other 'outside' samples. With the exception of sample Stuic 'outside' 5, the flaking index for 'outside' sites has a lower threshold value of 45.

The Stuic scree samples have a high proportion of category 2 type boulders, and a few category 1 type boulders representing completely fresh rockfall debris. Representations in categories 3 and 4 perhaps indicate the addition of well weathered boulders from the cliffs above. Weathering will have been acting upon the upper sections of the corrie back walls since, and during, the time the corrie glaciers were present. The fairly high representations in category 4 (11% and 21%) are possibly due either to the contribution of rocks which were weathering on the free face during or before the corrie glacier episode, or to the increased weathering of the rocks upon the cliff face as a result of their extreme exposure. The Stuic scree samples are in fact indicated by the granite weathering ratios to be more weathered than the boulders upon the floor of the Stuic corrie.

Summary and Conclusions

The results of the granite weathering ratio tests suggest that the extent to which the surface of granite boulders has decayed, in this area, is slight. Nevertheless, using a five category system of weathering indices, distinctive weathering ratios have been detected from different sites.

It is evident that much variation exists between different corries and between different 'outside' sites, the weathering ratios for some 'outside' sites often overlapping with the weathering ratios for other 'inside' sites. Despite this variation and overlap the ratios are distinctive between each pair, suggesting that although areal variations are apparent in the susceptibility or exposure to weathering of the rocks at the different sites, 'outside' sites are 'weathered' to a greater degree than their respective 'inside' sites.

The most diagnostic ratio was found to be the proportion of boulders in the granular stage of decay , to those in the flaking stage. Thus for 'inside' sites there was always more than 59% weathering by granular disintegration, and consequently less than 41% at the flaking stage. For 'outside' sites all but two samples indicate more than 65% at the flaking stage. The Cive corrie and Stuic 'outside' 5 samples were anomalies in this respect. In previous tests it has always been less 'weathered' than the other two Stuic 'outside' samples. In this test it only had 25% at the flaking stage, within the 'inside' ratio threshold. This sample was collected from large granite lobes near the lateral margin of the former corrie glacier and shows more affinity with the 'inside' samples than the 'outside' samples.

9.2b Sound Tests

Introduction and Previous Work

A modification of the granite weathering ratio technique was described by Kiver (1968).

The modified technique was based on the assumption that boulders in different stages of decomposition emit diagnostic sounds when struck with a hammer. Fresh boulders were described as giving a characteristic ring or "ping", and weathered boulders a duller "pong". According to Kiver this variation has been successfully used by other workers, but no published results are available. The ratio of fresh to weathered boulders was believed to be distinctive for each glacial advance as in the original technique.

Inconsistent results produced by using the conventional visual and sound methods led Kiver to abandon these in favour of recorded sounds. Tape recordings of boulder sounds in the field helped to eliminate inconsistency and personal bias. The recordings were analysed in the laboratory using an oscilloscope.

Sampling was restricted to medium grained granite or granite gneiss boulders between 0.33 to 1.33m diameter, on the surface of moraines. These restraints were imposed in order to minimize weathering differences resulting from mineral or rock size, different rock types, or the uncovering of fresher boulders by slope erosion. The same hammer was used throughout. Each boulder was struck twice in a uniform way with the microphone held 0.66m away. A close check was kept upon the position of the battery level meter to reduce variations of the speed during recording and playback.

Analyses of the tape recordings in the laboratory revealed a correlation between the emitted sound and pulse amplitude, frequency and duration. The amplitude readings were disregarded as identical battery voltages and volume settings had not been maintained during recording. Consequently, laboratory comparisons were found extremely difficult.

Fresh boulders were arbitrarily defined as those in which both pulses were greater than 0.3 seconds duration or those whose initial frequency was greater than 1,667 cycles per second for at least one of the pulses. It was found that weathering ratio counts could be duplicated to within 2 per cent if the power supply voltage remained unchanged. The attempts made in the laboratory to reset voltages to the crude estimates of level made in the field resulted in an average of 8 per cent for duration measures, and 15 per cent for frequency.

Kiver concluded that an improvement of the equipment, particularly the power supply, would serve to decrease the high variance and allow more measurement reliability. He also suggested that the transferance of the taped information to an oscillogram would permit rapid and exact measurements of pulse characteristics. This approach could provide more information, and also eliminate the binomial approach used in his study.

Aims of the Study

The experiment seeks to examine the sound transmitting characteristics of granite boulders in the study area, and to distinguish categories of rock disintegration upon the basis of measurable variations in some selected component, or components, of the recorded sounds. In order to introduce the technique more fully it is necessary to be familiar with the nature of sound and sounding bodies and the associated terminology.

Bases of the Technique - The Nature of Sound and Sounding Bodies

Sound is a mechanical wave motion in an elastic medium (Shortley and Williams, 1965). For sound to be produced a source is required to initiate a mechanical disturbance, and an elastic medium is necessary through which the disturbance can be transmitted. In the present experiment the source of the disturbance is a hammer, and the elastic medium is the granite rock sample.

When an impulse force is applied to the surface of a solid, energy is radiated from the source as two distinct types of elastic pulses of vibration (Stagg, 1968, p.145). The faster of these are known as longitudinal or compressional waves, the slower as transverse or shear waves. Compressional waves have particle displacements in the material only in the direction of travel of the disturbance. Shear waves have a particle displacement normal to the direction of travel of the disturbance.

All sounding bodies are in a state of vibration (Wood, 1949), and all elastic bodies can vibrate with a definite set of proper or characteristic frequencies corresponding to given boundary conditions (Morgan, 1964). It is the nature of the characteristic frequencies (the number of vibrations performed per second) and their duration (the length of time that elapses before they fade) that are of interest in the present study.

The ways in which a solid body can vibrate with all of its parts executing simple harmonic motion of the same frequency are called 'normal modes of oscillation of the body'. A general motion of vibration is a superimposition of normal modes having, in general, different frequencies (Shortley and Williams, 1965). The possible normal modes depend upon the shape of the body, its density, elastic properties and on the boundary conditions (the restraints imposed at the boundary of the body by other bodies in contact with it).

Complications are therefore introduced by the irregular shapes of the sampled boulders and their varying boundary conditions. Irregularly shaped rocks will have complicated resonance frequencies caused by the varying dispositions of the bounding faces. All the rocks sampled are resting upon the ground or upon other rocks, and as a result of their various irregular shapes will have differing proportions in contact with the ground or other rocks. The ground will damp out certain types of vibration, and the proportions of the rock in contact with other bodies has a critical effect upon the absorption of the waves.

The internal properties of the rocks themselves, their density and elastic properties, are dependent upon the initial nature of the granite, and the extent to which it has been affected by intergranular disintegration and chemical weathering. A change in the chemical composition of the rocks will cause a change in the velocity of the transmitted sound. Loss of contact between crystals will affect the sound by altering the length of the pulse. Such differences as a chemical change at the surface, micro-cracks, joints and other parting planes will influence the recordings. The volume of the rock does not affect the resonanance characteristics of the wave, but does influence its intensity and duration.

One of the primary advantages of field seismic techniques is that the seismic pulse is affected to a certain extent by the number and character of the discontinuities present. Thus a highly fractured or weathered rock will exhibit a lower compressional velocity than will a sound rock mass. The presence of water in the rock fissures also affects the velocity of the seismic pulses. Drying of the rock samples will result in a velocity decrease of up to 20% (Knill, 1970, p.95).

Stagg (1968) gave some typical seismic velocity for granite samples in different stages of decay:

		seismic velocity (m/sec).
granite :	massive	5,640
granite :	partly decomposed and slighlty seamed	3,200
granite :	highly decomposed and badly fractured	670
granite :	highly decomposed and friable	460

Laboratory studies of fresh biotite from Dartmoor (Duncan and Dunne, 1967) gave seismic velocity readings of from 2,130 to 3,030m /sec. The in situ jointed rock of Haytor gave readings of 1,640m/sec, and decomposed granite of 200-1,000m/sec.

Disadvantages

The waves produced in the rock by the hammerblow disturb the air as the rock vibrates. It is these disturbances that are picked up by the microphone. A certain amount of distortion of the waves inevitably occurs in their passage between the rock and the microphone. Other air disturbances, such as those created by the movement of the hammer, movement of the observer, the wind, animals, aircraft and the vegetation, disturbed by the observer or the wind, all produce disturbances that influence the microphone. Therefore the microphone does not only receive the unique vibrations of the rock, but all other local air disturbances are superimposed upon the final recording causing problems of interpretation.

If the rock is struck a glancing blow by the hammer, the elastic rock will be affected in a different manner than if a direct blow is applied. Such an indirect blow will produce slower transverse (Shear) waves.

The irregular shape of the rocks and their varying boundary conditions are a further source of variation in the recordings. It is almost impossible to sample boulders of exactly similar size and shape and boundary conditions. Each has its own unique size and shape, and each is placed in a different way upon varying proportions of other rocks, gravel, sand or peat.

Finally, no knowledge is available of the response of the fresh, unweathered Lochnagar and Mount Keen granites, or of the resonance characteristics of the hammer. The hammer resonates during the experiment, and this disturbance will be present upon the final record, as well as the air disturbances created by the observer when striking the blow, It would assist the interpretation procedure if the ideal responses of the hammer and rock were known.

It is recognised that there are a large range of seismic velocities even for well defined materials (Press, 1966). Velocity depends upon a large number of factors, among these are mineral composition, fluid content, temperature, grain size, cementation, direction with respect to bedding, foliation, or other structures, and alteration. At small depths and low pressures the velocity of compressional waves is significantly affected by the porosity of the sample. Drying of rocks results in a velocity decrease.

The velocity of the sound wave through the rock sample will influence its duration as recorded by the microphone. Unfortunately the present technique does not allow seismic velocities to be determined as the recording device is not in contact with the surface of the rock; thus, any attempts to determine wave velocity must take into account the passage of the sound wave through free air, and the distance it travels through the air. As the microphone was held by hand at only approximately similar distances from the rock in each case, such calculations are impossible from the present results.

The Present Study

The technique described by Kiver (1968) was further modified before being used in the south-east Grampian study area. Improvements were made in order to eliminate some of the problems encountered with the original equipment and interpretation methods used by Kiver.

The fundamental criticism was of the equipment. Better equipment was necessary, especially a more reliable tape recorder; "my recording equipment was not the best and I suspect that a tape recorder less subject to variations in motor speed and battery voltage would reduce the error considerably" (E.P.Kiver, pers. comm.) With this in mind a UHER '4000 Report-L' machine was selected for the present study. According to the manual describing the UHER "the exacting mechanical and electro-acoustic characteristics of this recorder will ---- qualify the UHER '400 Report-L' for all kinds of professional use". Variable motor speed was a serious mechanical error inherent in Kiver's tape recorder, but was almost completely absent in the UHER machine. A description of the machine's mechanical characteristics in the instruction manual states that; "the novel commutator free motor is distinguished by an extraordinary degree of reliability and speed stability".

Recordings were made at a tape speed of 9.5cm per second, upon E.M.I. type 825/9 extended play twin track professional recording tape. Available speeds were 2.4, 4.7, 9.5 and 19.0cm per second. The final recording speed was decided after advice (D. Cruickshank, pers. comm.), and confirmed by field tests of the technique and equipment carried out before the proper study began. These initial tests also assisted in the selection of the constant settings of the volume control, the tone and the modulation control, which were maintained throughout all the recordings. Thus it was hoped to eliminate the variability between recordings apparent in Kiver's study, which he pointed out were a result of his not maintaining identical volume settings on his tape recorder.

The UHER machine is powered by five dry cells of 1.5 volts each,so variations due to battery level differences were still possible. An intergrated recording level meter and battery voltage recorder fitted to the UHER was used frequently. Replacement batteries were carried in order to keep the voltage meter reading high.

Field sampling procedures were standardised as far as possible, to reduce variability caused by sample type and size, and recording methods. The study was confined to granite boulders of the medium grained biotite granite of the Lochnagar mass, and the Mount Keen granite. Boulder size varied from approximately 1.0 to 2.0m long.

The same hammer was used in all the recordings. It was swung in a consistent manner from shoulder height. A 'Grampian' outdoor microphone fitted with an optional plastic and foam windshield helped to reduce background noise to a minimum. Recording was only done on days when strong winds were absent, but great care was necessary to avoid recording when aeroplanes were passing overhead or moorland birds or deer were calling, all of which introduce background noises which affect the final sonograms. The microphone was held at approximately 0.5m from the area of rock being struck.

An attempt was made to improve the analysis technique by producing oscillograms as suggested by Kiver. Such print-outs allow the permanent records to be rapidly and easily analysed and compared, unlike the transitory screen displays of an oscilloscope.

Initially, print-outs were made using both a 'Kay Sona-Graph Machine', model 7029-A, and an 'Elema-Schonander Oscillograph'.The Kay Sona-Graph machine is an audio frequency spectrum analyser that produces permanent graphic recordings of any type of complex wave in the range 5-16,000 Hertz. 'Sonograms' are produced upon specially sensitised paper; for this reason print-outs are expensive to produce. A sonogram is an overall three-dimensional picture of the signal being analysed, on which frequency, amplitude and time are represented simultaneously upon one display. The'Elema-Schonander Oscillograph' is a 16 channel ink-jet recorder that produces sonograms displaying wave amplitude and duration. High frequency response spray pens produce graphical wave traces upon continuous paper strips.

Field Sampling

The field sampling procedure followed closely that adopted in the previous three weathering studies, but this technique was not applied to the Cive corrie, only the Stuic, Lochnagar and Mount Keen corries were examined. Each sample consisted of fifty boulders, except for the Stuic scree sample which was made up of only twenty five, and no duplicate sampling was performed in the Stuic corrie as in the previous tests.

Results

Print-outs produced in the laboratory from the field tapes were examined for any characteristic changes in the amplitude, frequency and duration of the pulse.

Amplitude: Measures of pulse amplitude were not used in the present study as play-back of the tapes revealed variations in the volumes of the recorded sounds within sample groups and even between duplicated recordings from the same sample. These variations could be due to a combination of factors. In the case of the variations apparent within groups errors could be introduced by changes in battery voltage, accidental changes in the volume and/or tone controls when setting down the tape recorder upon rough ground, faulty connection of the microphone, changes in the distance or direction of the microphone from the rock, movement of the microphone during striking or perhaps an intermittent fault within the tape recorder itself. Mains voltage was used in the laboratory for play-back of the tapes so some distortion of the sounds would result if the battery voltages had been low at the time of recording. Variations between duplicated hits from the same sample are most likely a result of a change in the direction or distance of the microphone during or after one or both of the hits. In many cases the first hit produced a shower of loosened, weathered grains. A second hit upon the same place met more solid rock and so produced a sound of slightly higher amplitude. The sound and spray of the shattering is often apparent upon the print-outs (Fig 9.7).

In some instances the sound pulse recorded from the rock is difficult to separate from the effects of wind in the microphone, the background noise being of similar amplitude to the rock-sound.

For amplitude measurements to be accurately made, the quality or accuracy of the recordings require to be still further improved, especially by filtering out background noise, and reducing the possibility of changes in the position or orientation of the receiver influencing the recorded sound.

Frequency : Problems also arose when attempting to analyse the frequencies of the recorded pulses. The sonogram (Fig 9.6) produced upon the Kay-Sona-Graph illustrates some of the difficuties.

At each end of the sonogram are frequency markers. The centres of each dark bar are situated at intervals of 500 Hertz (cycles per second), thus the scales on Fig 9.6 extend from 0 to 8,000 Hertz. It is apparent from the sonogram that the initial maximum frequency

Is in excess of 8,000 Hertz.

The initial disturbance extends through all frequencies, up to and above 8,000 Hertz, and lasts for about 0.025 to 0.035 seconds. The trace then resolves into four dark traces at different frequencies. These dark bands are not completely understood (R. Hipkin, pers. comm. and D. Cruickshank, pers. comm.). They appear to represent resonant frequencies; that is, the sample or some element of the field equipment supported oscillations at three or four different frequencies. These frequencies are approximately 0-500, 2,200-2,800, 4,400-5,200 and 7,000-7,300 Hertz .

The two highest frequency oscillations appear to be rather transient, only the second lower frequency (2,200-2,800 Hertz) being sustained for very long. This lasts for a total of about 0.095 seconds from the initiation of the disturbance, and shows a fade period of about 0.015 seconds. As stated previously(in the Bases of the Technique section) the normal modes of oscillation depend upon a variety of factors including the shape of the body, its density, elastic properties and the boundary conditions. It is apparent that these frequencies are a result of a variety of factors other than simply the changing density and elastic properties of the rock as it weathers.

A further complication is introduced by the fact that the hammer will also resonate and so its characteristics will be superimposed upon the record, and so contained within the trace seen in Fig 9.6. Thus the initial disturbance will include the resonance of the hammer. As the hammer will remain within the audible range of the microphone for the 0.10 seconds, or less, duration of the traces, at least one of the resonance 'bars' of the trace will represent the resonant frequency of the hammer. It appears desirable that the resonant frequency (s) of the hammer should be determined before any specific conclusions can be drawn concerning the resonant frequencies supported by the different rock samples.

It is apparent that at this stage in the understanding of the complexities of the technique, any attempt to analyse the frequency variations of the rock samples is accompanied by too many unknowns to allow any satisfactory conclusions.to be drawn.

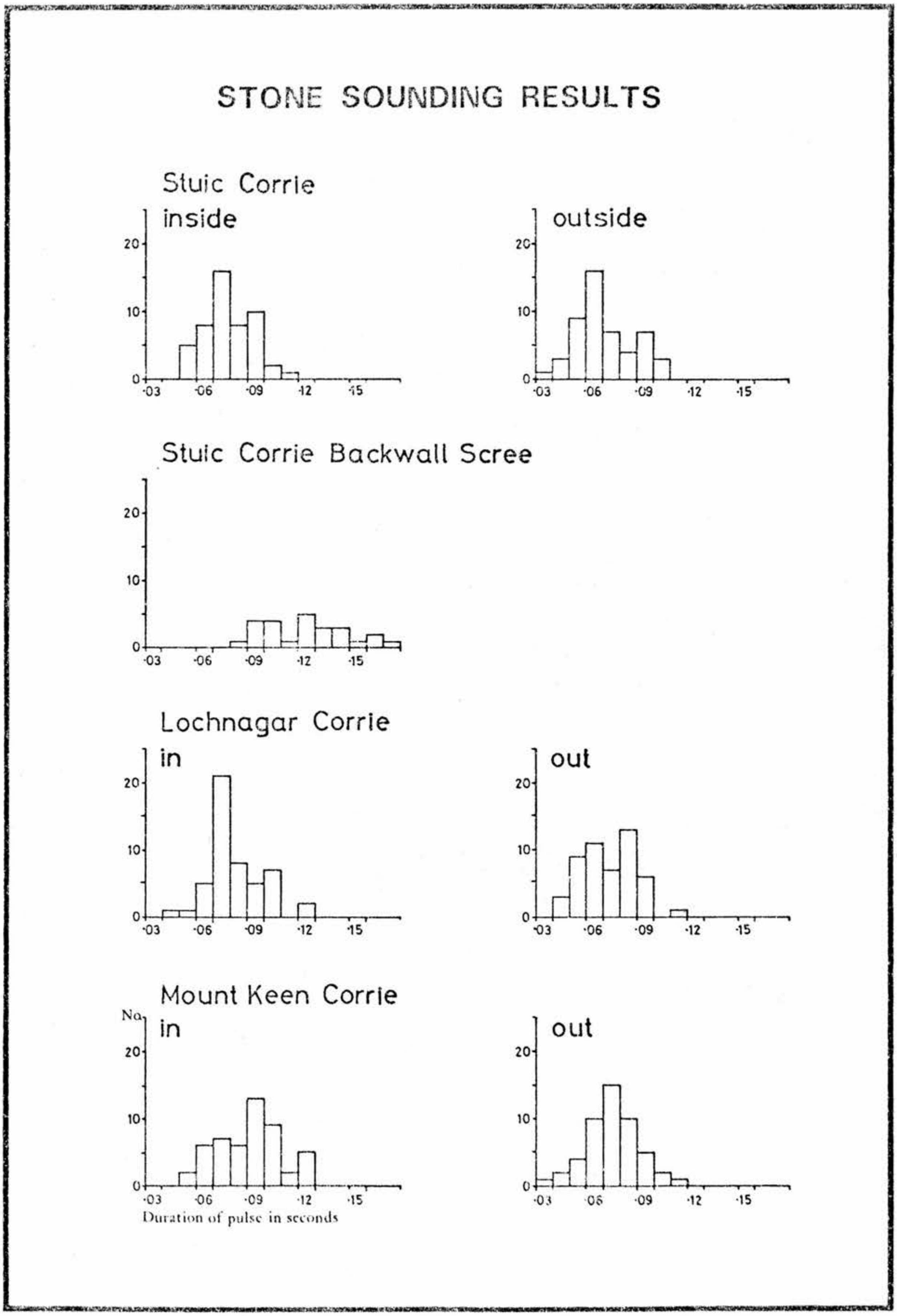

STONE SOUNDING RESULTS
Stuic Corrie
inside
outside
Stuic Corrie Backwall Scree
Lochnagar Corrie
in
out
Mount Keen Corrie
No.
in
out
0
10
20
·03
·06
·09
·12
·15
Duration of pulse in seconds

Figure 9.5

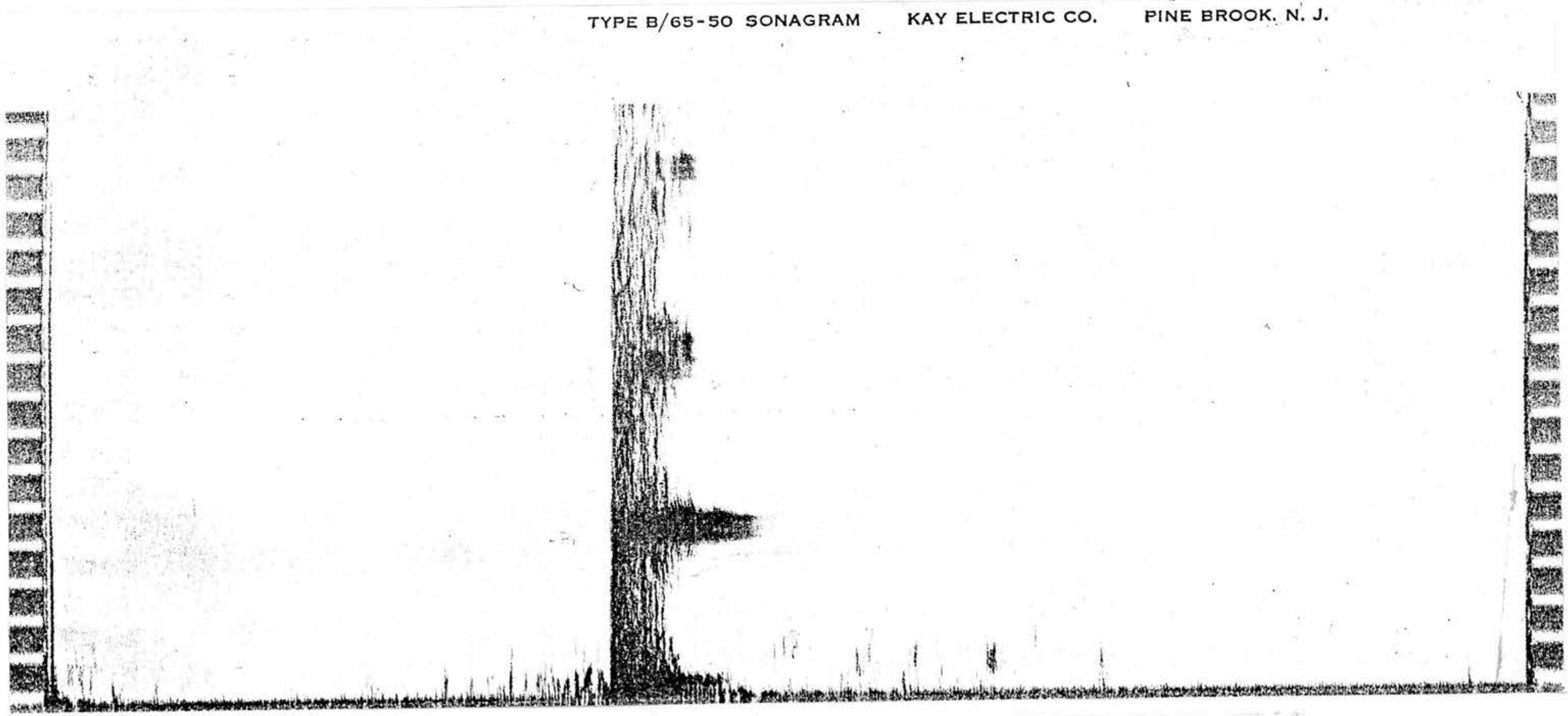


FIGURE 9.6 An example of a Kay Sonogram print-out. At each end of the sonogram are frequency markers. The centres of each dark bar are situated at intervals of 500 Hertz (cycles per second). The duration of the pulse is measured along the base of the sonogram: ten inches represent one second. This pulse, from 'inside' the Lochnagar moraine (boulder No.9), had an approximate maximum duration of 0.095 seconds at between about 2,200 to 2,800 Hertz.

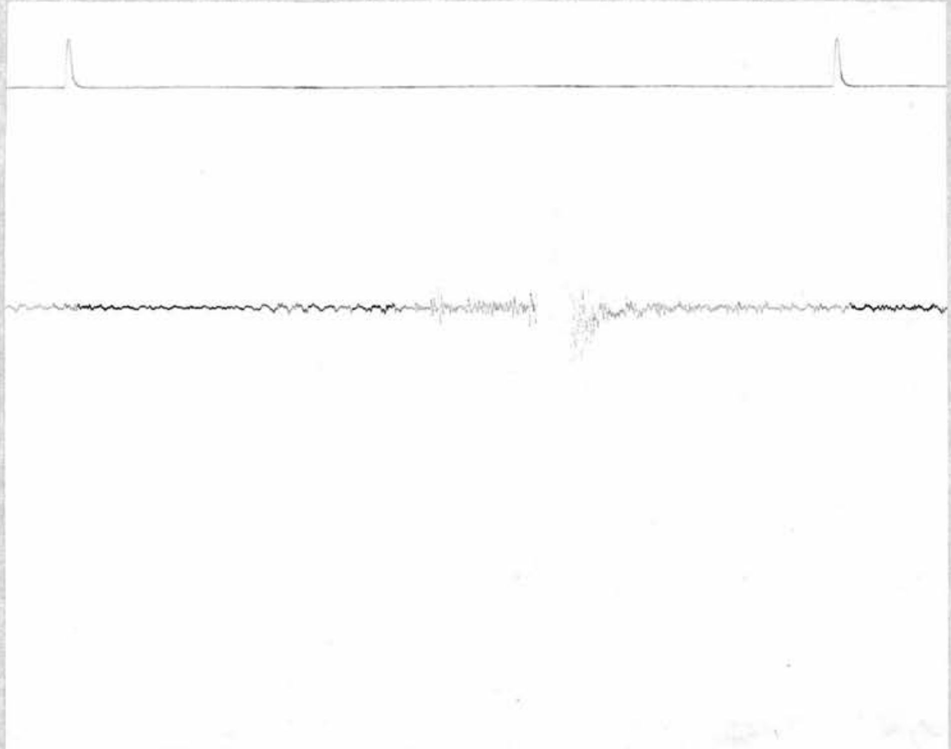
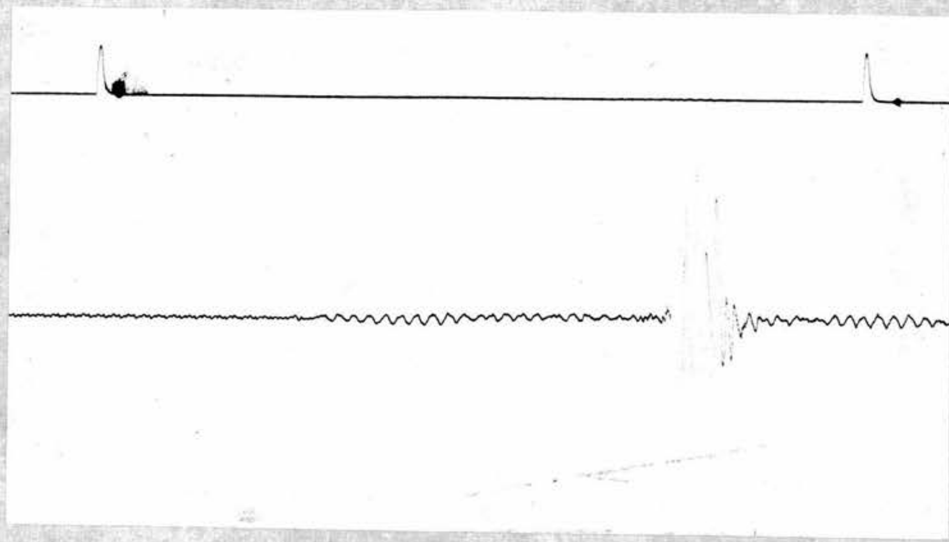


FIGURE 9.7 An Elema-Schonander Oscillograph. This example illustrates a wave of 0.08 seconds duration, from an 'outside' site (Lochnagar 'outside' No.24). The re-intensification of the wave-form in the last 0.02 seconds is the sound of spraying of shattered granite fragments after the hit.

The horizontal scale, the pulse duration, is shown by the markers on the upper line at 1 second intervals 10cm = 1 second.



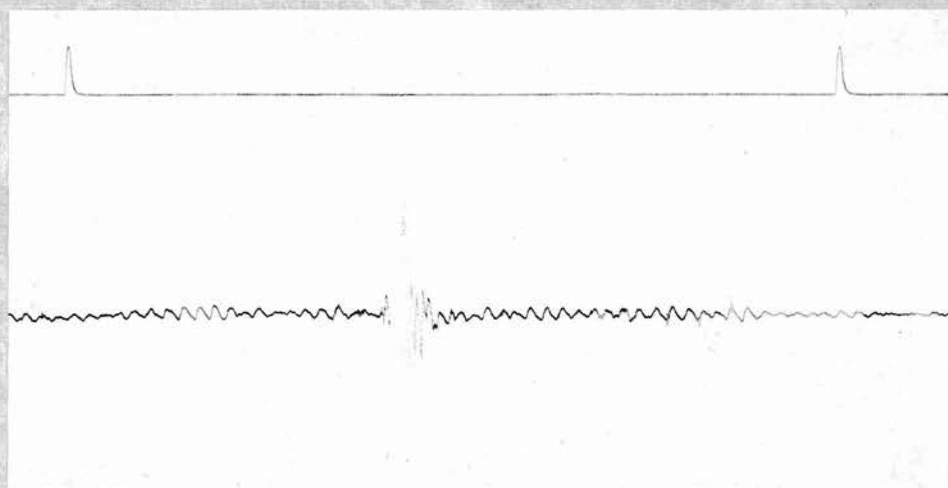


FIGURE 9.8 Elema-Schonander Oscillographs to illustrate the different pulse durations between 'inside' and 'outside' sites, from the Mount Keen samples ('Inside' No.5 and 'Outside No.40). The 'inside' sample (top) is of 0.09 seconds duration and the 'outside' sample (bottom) is of 0.07 seconds duration (the mode for each site).

<u>Duration</u>: Measurement of the duration of the pulse appears, at present, to offer the most reliable index for categorising the samples. The length of time over which the disturbance is sustained by the rock will vary depending upon many factors, including the amount of intergranular disintegration and chemical weathering, micro-cracks and other joints present, and also the volume of the sample. Sampling was intentionally restricted to blocks of a fairly limited size range (1-2m long), so that variations due to volume differences were minimised as far as possible. The technique is then based upon the premise that the duration of the sound varies between samples as a direct result of changes in the composition and coherence of the rock.

Fresh boulders were arbitrarily defined by Kiver (1968) as those in which (both) pulses were greater than 0.03 seconds duration. Upon this basis all the rocks sampled during the present study could be considered to be fresh, only two examples from the 325 tested had pulses lasting for as little as 0.03 seconds; both these were from 'outside' situations (Stuic 'outside' and Mount Keen 'outside') (Fig 9.5).

Pulses ranged at the maximum from 0.04 to 0.12 seconds in the 'inside' samples, and from 0.03 to 0.11 seconds in the 'outside' samples. The Stuic scree sample had a range of from 0.06 to 0.17 seconds (Fig 9.5). The 'outside' samples tend to have a greater number of boulders with pulses of low duration, the opposite being the case in the 'inside' samples.

Discussion of the Duration Results

It appears from the results that the boulders in 'inside' situations are able to support the induced sound disturbances for slightly longer periods, on average, than those in 'outside' situations (Figs 9.5 and 9.8). The summary results are presented below.

		Inside	Outside	Difference
Stuic	mode	0.07	0.06	
	av.	0.0764	0.0679	0.0085
Scree	mode	0.12		
	av.	0.1216		
Lochnagar	mode	0.07	0.08	
	av.	0.0789	0.07	0.0089

Mount Keen	mode	0.09	0.07	
	av.	0.0884	0.0719	0.0165

Although the modal value of the Lochnagar 'outside' sample is higher than the modal value of the Lochnágar 'inside' sample, the averages of the two samples show a difference similar in amount and direction to the Stuic sample pairs. Fig 9.5 shows that the Lochnagar 'outside' sample has a secondary mode at 0.06 seconds.

All 'inside' samples have an average pulse duration of more than 0.075 seconds, and all 'outside' samples an average pulse duration of less than 0.072 seconds.

If a pulse duration of 0.06 seconds or less is selected as defining weathered boulders, then the 'inside' samples are characterised by having 26% or less of weathered boulders, and the 'outside' samples 34% or more.

	Inside	Outside
Stuic	26/74	58/42
Lochnagar	14/86	46/54
Mount Keen	16/84	34/66
Scree	0/100	

Between each sample pair, the number of 'weathered' boulders in the 'outside' samples is more than double the number in the corresponding 'inside' sample.

The populations of each sample pair are statistically different at the 97.5% level (Kolmogorov-Smirnov). Statistically there is no difference between the 'outside' samples, thus they appear to have been drawn from the same population. The Stuic and Lochnagar 'inside' samples are not statistically distinct, but both are distinguishable from the Mount Keen 'inside' sample at the 95% confidence level. An examination of the modal and average values for each of the 'inside' samples reveals that the Mount Keen 'inside' sample has higher modal and average values than the other two; thus it differs from them in having a greater frequency of higher duration values, that is the sample appears to be less weathered than the other two.

Summary and Conclusions

It has been shown that the sonogram print-outs produced from the field tapes cannot be reliably interpreted in terms of pulse amplitude and frequency because of the level of extraneous noise in many recordings, and the seemingly random and unaccountable variations of volume and quality between recordings, despite careful attempts to refine the technique. Difficulties were also encountered in interpreting the significance of many features of the sonogram.

Pulse duration was found to be less subject to such disadvantages and so this was selected as the diagnostic characteristic. The duration of the pulses was measured upon paper traces produced using an Elema-Schonander Oscillograph.

'Inside' sites were characterised by pulses of 0.04 to 0.12 seconds duration, and having 26% or less of the sample with pulses below 0.06 seconds duration. 'Outside' sites ranged from 0.03 to 0.11 seconds, and had 34% or more of the sample below 0.06 seconds duration.

Thus the results of the duration measures suggest that the boulders in the 'outside' sites are slightly more 'weathered' than those in 'inside' sites.

Suggestions for Improvements to the Technique

An important criticism of the technique is the separation, by a zone of free air, of the vibrating rock mass and the recording microphone.

More energy would be retained in the recording system if the rock/air interface could be precluded, as the waves are affected by their passage through the air and other external air disturbances are superimposed upon the recording. If direct readings could be made upon the surface of the rock, extraneous disturbances and distortion would be almost completely eliminated. The use of a strain-gauge or seismometer seems to be the most feasible alternative. A strain gauge would record the amount of surface distortion of the rock, but it could be influenced by where it was placed in relation to areal variations in the nature of the rock surface, if local differences were significant. This would be especially important if the rock was crossed by minute parting planes.

The use of a hammer, which also resonates, is also a problem which influences the recordings. It is possible to determine the resonance characteristics of the hammer by shooting a small missile, such as a steel ball bearing, at the hammer freely suspended beside a microphone. This would allow the resonances of the hammer to be recorded, and only minimally pick up the resonances of the missile which would rapidly bounce or fall from the audible range of the microphone. The resonances of the hammer could then be identified upon the final recordings and allowances made for isolating its effect.

A further, more desirable modification would be to eliminate the use of a hammer completely, and thus the hammer resonances from the record, and prevent the possibility of peculiarities being introduced by blows of varying angle and intensity. In place of the hammer a transducer could be used, preferably bonded to the rock surface. This device produces a pulse of known frequency, allowing complete reproducibility between sites and providing a source of constant and known characteristics.

The response of the fresh Lochnagar and Mount Keen granite could be determined using laboratory experiments conducted in carefully controlled conditions. A similar laboratory set-up could be used to test the response of weathered samples, from the field, to establish the notable seismic characteristics of weathering rock. Such experiments have been performed upon short cylindrical specimens of rock to test the velocity of compressional waves (eg. Birch, 1960, 1961) and shear waves (eg.Simmons, 1964) using ultra-sonic pulse instruments which generate pulses of known frequency. Such an approach would provide valuable information about the response of these rocks under ideal conditions, but should only be used as a supplement to the field technique, to assist it and not replace it, as the aim of the study is to provide a field method of widespread application.

From the present results it was found to be impossible to compensate for the varying boundary conditions and the irregular shapes of the rocks.It is suggested that some attempt be made to locate rocks with as exactly similar boundary conditions and shapes as possible. Several groups of like nature could be sampled, then the groups compared. The laboratory tests should be intimately linked to these controlled field tests to provide the maximum information.

Finally it is apparent that the introduction of some sort of timing device would allow the velocity of the waves to be determined. Combined with the other modifications described, especially the use of a transducer to produce a pulse of known frequency, the travel time of the wave through the sample could be accurately determined, as also its total duration and distortion.

These problems and their suggested solutions and refinements to the technique were brought to light during the present study which began upon the basis described by Kiver (1968).

Overall Summary and Conclusions

Four different tests were devised to measure the extent to which subaerial weathering processes had affected granite boulders. The tests were concerned with the amount of edge and corner rounding of the blocks, and the extent of surface and subsurface decay of the rock fabric. These tests were applied to granite boulders in situations 'inside' and 'outside' the presumed limits of four former Loch Lomond corrie glaciers upon the Lochnagar and Mount Keen Massifs of the south-east Grampian Mountains.

The results revealed that in every case the granite boulders 'outside' a particular glacial limit were more weathered than those at a site 'inside' the same limit. Areal variations were apparent in the amount of 'weathering' at different 'outside' sites, and between 'inside' sites from the different corries. Similar differences were also detected between samples selected from sites having varying altitude and exposure characteristics, 'outside' the same moraine. Despite such areal variations, 'outside' sites generally showed more affinity to each other than to any 'inside' site, and vice versa. These findings suggest that the granite boulders occurring outside the limits of the four former corrie glaciers are more 'weathered' than boulders occurring inside the moraines.

Each of the four studies revealed that the total amount of weathering that had occurred upon the granite boulders of the area was relatively slight. Consequently the differences in the amount of weathering between 'inside' and 'outside' sites was of a small order.

It can be concluded from the findings of the four weathering studies that during the post-glacial period, subaerial weathering processes have had a slight effect upon the granite boulders of the south-east Grampian study area. Although the total amount of weathering accomplished is only slight, areal variations in the effects of weathering have been detected. The most marked areal difference has been shown to occur between samples at sites 'inside' and 'outside' the presumed limits of the Loch Lomond corrie glaciers. This difference can be most satisfactorily explained by assuming that the areas 'inside' the presumed glacial limits were swept clear of existing superficial boulders by the Loch Lomond readvance ice. In consequence, any boulders presently occurring within the glacier limits have only been weathering since the corrie glaciers decayed, about 10,300 years ago (Sissons, 1974b, p.319). There is considerable evidence suggesting that the total deglaciation of Scotland, from the ice sheet, was completed by 12,500 B.P. (Sissons, 1974b, p.315). Thus any boulders occurring outside the limits of the Loch Lomond readvance corrie glaciers will have been exposed to subaerial weathering for about 12,000 years.

These dates indicate that the granite boulders in 'outside' sites have been weathering subaerially for about 12,000 years, while those in 'inside' sites have only been exposed for about 10,000 years, or for approximately 2,000 years less. Upon this basis the differences in the degree of weathering between the two groups would be expected to be slight.

CHAPTER 10

Summary and Conclusions

The preceding study has demonstrated that boulder lobes and gliding boulders are the most frequently occurring periglacial features in the south-east Grampian study area. Boulder terraces were observed, but these are rare. Rockfall and avalanche processes are currently operative upon free faces and snow accumulation slopes.

It is suggested that subaerial weathering processes have been modifying granite boulders situated 'outside' the mapped limits of the presumed Loch Lomond age corrie glaciers since the final melting of the Scottish Ice-Sheet, about 12,500 years ago. Granite boulders situated 'inside' these presumed limits are 'less-weathered', a finding that supports the suggestion that active corrie glaciers have occupied these corries since the disappearance of the ice-sheet, clearing out and modifying the previously weathered debris. Thus granite debris 'inside' the corrie moraines has only been exposed to subaerial weathering since the end of the Loch Lomond Stadial, at about 10,300 B.P.. The small magnitude of the differences between the 'inside' and 'outside' sites precludes the possibility that active glaciers could have occupied the corries in the more recent past.

The distribution of granite boulder lobes also accords with the above findings. Boulder lobes are widespread throughout the Lochnagar and Mount Keen granite areas, but are absent from ground inside the mapped corrie glacier limits. Individual lobes and lobe series terminate abruptly at the lateral limits of the former glaciers at several locations. It is inferred from this relationship, combined with the detailed results derived from the study of the nature of these lobes, that they developed during the climatic deterioration associated with, and preceding, the Loch Lomond Stadial. An absence of lobes inside these limits and the abrupt downslope termination of lobes at the lateral limits indicates that climatic conditions have not been suitable for the renewed development or movement of granite boulder lobes since the Loch Lomond Stadial.

Outside the mapped glacial limits the boulder lobes are developed on slopes of all aspects between 011° and 357°. The absence of lobes on north-facing slopes is probably a result of a lack of frequent temperature fluctuations upon slopes of this aspect inhibiting the development of interstitial ice in the coarse granite debris, and so preventing considerable movements of the regolith. Lobes appear to prefer west-facing snow free slopes, away from the insulating effects of late-lying snow patches. Gliding boulders are developed upon slopes of all aspects and appear to show no preference for slopes of any particular aspect.

Lobes and gliding boulders are developed upon slopes of similar angles. Lobes were found on slopes between 10° and 34° gradient and gliding boulders on slopes between 9° and 38°. Tests have shown that these groupings indicate the slope angles favoured by these features, and are not simply a reflection of the slope angles available in the respective sampling areas. The upper altitudinal limit of both features was at about 1100m, the highest point of the study area. Gliding boulders were found down to the lowest altitude examined, at 450m, but lobes were only found down to 580m. The nature of the slope vegetation appears to have little influence upon the development of gliding boulders. Vegetation post-dates the formation of the granite lobes.

Comparisons of the size of lobes, and the size of gliding boulders, developed in the granite and metamorphic areas revealed that the metamorphic features are usually smaller, largely due to the smaller debris in that area. Metamorphic gliding boulders were found in quartzite, schist and gneiss areas but metamorphic lobes were only found in quartzite areas.

Granite lobes are fossil features, formed of huge granite debris that, it is suggested, is only capable of moving by a process analogous to rock glacier creep, which requires the formation of interstitial ice. Quartzite lobes are similarly devoid of interstitial fine material and appear to be relatively stable at the present day.

The scarcity of terrace features in both granite and metamorphic terrains is considered to result from the coarse nature of the granite and quartzite debris. The development of interstitial ice in the regolith would probably occur in favoured zones, thus causing zones of more rapid flow and leading to the development of lobes. Uniform sheet flow or creep is less favoured in this coarse debris, evidenced by the scarcity of terraced forms, than in finer-grained materials in other areas.

Gliding boulders are active, in both terrains, at the present day. They were recorded as moving up to 2cm/year between 1971 and 1975, but movements of less than 1cm/year were more common. The application of dendrochronological technique in four sample furrows provided estimates of gliding boulder movements over the recent past. These investigations suggested that gliding boulders have been travelling at about their currently measured rates for the last 7 or 8 years, but appear to have travelled faster than this between about 8 and 20 years ago.

Rockfalls and avalanches are more active in this area than has previously been recognised. Nine rockfalls occurred from the walls of corries in the Lochnagar Massif between 13 June and 1 August 1972, the largest involving almost 4 tonnes of granite debris. Rockfalls are thus an important and regular process contributing to the development of the large postglacial screes in the corries. Avalanches and cornice-falls are frequent upon lee slopes after heavy snow falls. They act more in a transporting capacity than an eroding capacity, moving loosened debris down open slopes and chutes. Their effectiveness is limited by the lack of available relief and the infrequency of large snowfalls on an Alpine scale.

CHAPTER 11

Suggestions for Further Work

1. Lobes

Investigation of the internal composition of the large granite and quartzite lobes was prevented by the coarse nature of the regolith. The application of seismological techniques would allow an investigation of the depth of the boulder layer and determine if fines are present in any of the lobes, or at a depth below their surface. This information is necessary for an understanding of the mode of formation of these features.

2. Gliding Boulders

The present study suggested that the nature of the sliding surface of gliding boulders might have an important influence upon the rate, and existence of boulder movement. This could be examined in future surveys.

Movement experiments could valuably be extended to include a larger number of examples in a wider range of environmental situations to assist the delimiting of factors controlling gliding boulder movement. These studies should be combined with studies of the particle size distribution of the regolith in the path of the boulder, and preferably involve continuously recording meteorological instruments at the immediate sites, combined with regular periodic checks of possible boulder movements.

Placing of standardised concrete or composition blocks adjacent to currently active gliding boulders might aid an understanding of the influence of environmental factors upon the movement of blocks of known characteristics.

3. Boulder Weathering Studies

These studies could be usefully extended to other granite, and also gneissic areas to develop the technique in different situations.

The tape recorder technique requires further development and refinement, particularly with regard to the use of a constant pulse source and a recording device attached to the rock in order to minimise error and background noise. Further knowledge of the responses of fresh and unweathered granite samples, determined in closely controlled laboratory experiments, is required to interpret the complex Kay-Sonograph patterns. Detailed refinements may allow the distinction of weathering zones within the granite boulders.

Further studies in the present areas are desirable in order to determine the full extent of the possible areal variations between samples from sites 'inside' and 'outside' the same moraines.

4. Rockfalls and Avalanches

Short-term observations suggested that rockfalls occur frequently in the Lochnagar corries. More intense observations combined with rockfall sampling 'mats' or quadrats on screes and below free faces, and other collecting devices suitably located, would provide valuable and positive results about the rate of post-glacial cliff recession in this area.

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APPENDIX I

Boulder Lobe Field Measurements

Key to the columns:

A. Number

B. Altitude (metres above sea-level)

C. Slope Aspect (degrees magnetic)

D. Slope Angle (degrees from the horizontal)

E. Angle of the lobe surface (degrees from the horizontal)

F. Angle of the ground below the riser

G. Angle of the riser

H. Length of the lobe (tenths of a metre)

I. Width of the lobe (tenths of a metre)

J. Length of the riser (tenths of a metre)

K. Length of the left-hand lobe side (tenths of a metre)

L. Length of the right-hand side (tenths of a metre)

M. Lithology 1 - granite 2 - metamorphic

N. Thickness of the lobe-layer (tenths of a metre)

Granite Sample 1. Lochnagar

Meall an Tionail (NO 223876)

A	B	C	D	E	F	G	H	I	J	K	L	M	N
001	0770	270	29	23	25	35	0289	176	087	----	----	1	15
002	0760	272	28	30	25	40	0213	157	122	----	----	1	32
003	0770	276	29	29	25	39	0328	212	104	----	----	1	25
004	0760	284	29	27	25	36	0215	114	061	----	----	1	12
005	0760	287	27	27	26	37	0255	101	055	----	----	1	11
006	0790	270	23	21	21	35	0259	266	068	----	----	1	16
007	0790	266	23	23	21	35	0239	174	059	----	----	1	14
008	0730	266	25	26	23	35	0243	198	054	----	----	1	11
009	0740	244	25	25	23	34	0411	212	131	----	----	1	25
010	0740	243	25	26	24	32	0221	156	143	----	----	1	20
011	0730	243	25	23	25	31	0223	218	082	----	----	1	09
012	0730	240	25	25	25	34	0214	122	108	----	----	1	17
013	0750	236	25	23	25	34	0243	125	046	----	----	1	07
014	0750	234	25	20	23	34	0298	126	052	----	----	1	10

015	0780	270	27	21	26	36	0276	261	057	---	---	1	10
016	0760	270	27	30	26	37	0213	154	094	---	---	1	18
017	0760	269	27	32	26	34	0146	117	084	---	---	1	12
018	0770	268	28	29	25	32	0214	108	104	---	---	1	13
019	0780	266	27	26	25	34	0133	147	085	---	---	1	13
020	0760	263	29	25	23	38	0289	162	092	---	---	1	24
021	0790	291	23	21	15	25	0397	208	068	---	---	1	12
022	0790	296	23	20	09	32	0309	148	032	---	---	1	13
023	0780	298	23	19	08	34	0281	174	039	---	---	1	17
024	0800	296	23	24	19	33	0235	136	078	---	---	1	19
025	0800	294	23	23	20	32	0282	158	076	---	---	1	16

Cnapan Nathraichean (NO 223888) (includes Creag Liath and Meall Coire na Saobhaidhe: 066 - 075)

026	0710	226	20	22	12	32	0307	138	038	---	---	1	13
027	0710	226	20	20	10	29	0157	180	058	---	---	1	19
028	0700	238	20	15	08	27	0254	178	063	---	---	1	21
029	0730	232	22	20	15	25	0152	111	047	---	---	1	08
030	0730	248	22	24	13	26	0148	089	082	---	---	1	19
031	0730	249	19	21	20	27	0114	088	050	---	---	1	06
032	0740	232	21	16	17	28	0147	166	044	---	---	1	08
033	0740	230	21	20	15	22	0263	161	052	---	---	1	06
034	0750	224	19	23	10	25	0477	172	067	---	---	1	17
035	0750	218	19	20	14	21	0336	143	091	---	---	1	11
036	0760	206	19	21	13	24	0452	189	058	---	---	1	11
037	0780	236	17	23	10	32	0346	201	040	---	---	1	15
038	0770	230	18	25	14	30	0655	149	067	---	---	1	19
039	0770	224	18	22	15	26	0561	277	056	---	---	1	11
040	0770	222	19	21	17	23	0308	143	052	---	---	1	05
041	0780	240	17	18	16	20	0241	173	084	---	---	1	06
042	0780	288	19	17	13	26	0215	097	055	---	---	1	12
043	0800	218	14	12	12	28	0152	124	026	---	---	1	07
044	0800	216	15	16	12	29	0163	118	076	---	---	1	22
045	0810	236	14	18	14	23	0231	092	042	---	---	1	07
046	0700	282	20	23	12	31	0316	152	043	---	---	1	14
047	0700	283	20	25	13	36	0282	097	022	---	---	1	09
048	0710	286	22	21	11	32	0114	063	042	---	---	1	15

049	0720	285	22	21	20	32	0225	140	061	---	---	1	13
050	0720	286	22	22	14	31	0319	118	022	---	---	1	06
051	0760	246	16	15	12	28	0138	096	034	---	---	1	09
052	0780	246	16	13	15	27	0206	094	046	---	---	1	10
053	0770	244	18	15	15	31	0124	059	039	---	---	1	11
054	0770	232	17	15	14	25	0116	060	027	---	---	1	05
055	0790	242	18	17	16	24	0112	099	051	---	---	1	07
056	0690	256	21	19	15	30	0397	199	046	---	---	1	12
057	0700	274	21	24	14	28	0265	160	062	---	---	1	15
058	0700	268	21	24	21	34	0259	138	059	---	---	1	13
059	0710	278	20	24	20	32	0483	217	138	---	---	1	29
060	0710	280	20	22	23	32	0188	179	048	---	---	1	08
061	0710	282	20	24	20	34	0252	120	036	---	---	1	09
062	0720	276	21	19	15	33	0143	118	046	---	---	1	14
063	0720	274	22	21	19	28	0170	111	041	---	---	1	06
064	0720	270	20	19	18	31	0287	120	063	---	---	1	14
065	0720	272	20	20	22	30	0178	167	058	---	---	1	08
066	0720	274	20	23	23	31	0144	098	047	---	---	1	07
067	0730	270	21	26	16	30	0317	099	040	---	---	1	10
068	0740	238	19	18	14	29	0280	106	052	---	---	1	14
069	0760	234	19	19	12	29	0202	085	088	---	---	1	26
070	0770	240	19	18	15	30	0375	090	024	---	---	1	06
071	0780	264	16	14	13	28	0184	065	041	---	---	1	11
072	0740	274	20	22	17	29	0468	094	043	---	---	1	09
073	0740	282	20	23	16	29	0422	113	051	---	---	1	12
074	0750	284	23	25	16	27	0288	141	048	---	---	1	09
075	0750	286	22	19	20	32	0081	067	045	---	---	1	09
076	0810	253	22	15	19	29	0172	103	044	---	---	1	08
077	0810	252	22	18	21	25	0137	106	073	---	---	1	05
078	0800	321	22	12	15	28	0096	047	033	---	---	1	07
079	0790	320	22	15	14	25	0043	039	027	---	---	1	05
080	0790	350	22	18	16	26	0069	057	066	---	---	1	12
081	0790	012	22	12	17	28	0143	101	075	---	---	1	14
082	0780	018	22	18	19	27	0170	062	079	---	---	1	11
083	0810	345	16	12	13	26	0149	128	087	---	---	1	20
084	0770	354	23	21	23	30	0089	073	047	---	---	1	06
085	0770	316	23	16	17	27	0099	074	104	---	---	1	18

086	0780	316	22	12	16	26	0100	078	020	---	---	1	04
087	0760	316	22	17	14	29	0080	056	059	---	---	1	15
088	0750	314	22	14	17	30	0130	058	066	---	---	1	15
089	0750	318	20	18	11	29	0221	134	023	---	---	1	07
090	0750	226	23	23	12	28	0343	092	037	---	---	1	10
091	0750	277	17	15	10	28	0150	054	067	---	---	1	21
092	0760	286	24	18	18	36	0249	138	049	---	---	1	15
093	0760	252	20	18	15	30	0098	066	030	---	---	1	08
094	0760	276	22	23	19	35	0279	078	117	---	---	1	32
095	0750	283	19	18	14	32	0317	146	034	---	---	1	11

Cuidhe Crom (NO 260848)

096	0850	103	24	29	25	30	0339	093	062	---	---	1	05
097	0850	092	24	28	22	34	0430	234	041	---	---	1	09
098	0850	091	24	29	24	31	0105	077	103	---	---	1	13
099	0850	090	25	33	25	34	0180	137	096	---	---	1	15
100	0860	116	23	28	21	32	0121	113	060	---	---	1	11
101	0870	117	23	23	16	34	0478	112	061	---	---	1	19
102	0840	094	24	25	21	25	0335	161	118	---	---	1	08
103	0990	062	23	25	17	30	0210	322	171	---	---	1	39
104	0980	063	23	28	19	35	0413	269	173	---	---	1	48
105	1000	046	21	24	17	31	0466	132	112	---	---	1	27
106	1010	036	21	20	15	29	0230	137	115	---	---	1	28
107	1000	088	21	24	15	29	0436	117	051	---	---	1	12
108	1000	091	20	20	18	30	0310	140	133	---	---	1	28
109	0970	075	25	27	23	35	0160	110	121	---	---	1	25
110	0970	057	22	20	23	31	0355	216	110	---	---	1	15
111	0890	082	17	16	17	22	0215	094	086	---	---	1	08
112	0910	072	18	17	18	26	0172	079	043	---	---	1	06
113	0930	076	18	22	18	27	0271	140	053	---	---	1	08
114	0930	078	18	19	18	24	0142	085	043	---	---	1	05
115	0920	072	18	18	16	22	0184	086	044	---	---	1	05
116	0940	074	19	21	18	25	0145	073	060	---	---	1	07
117	0920	078	20	18	18	24	0115	066	038	---	---	1	04
118	0940	094	20	17	16	35	0444	142	100	---	---	1	33
119	0950	090	22	20	15	27	0139	070	070	---	---	1	15
120	0960	084	22	20	21	37	0585	180	045	---	---	1	12

Meikle Pap (NO 260860)

121	0890	086	22	23	19	27	0135	095	079	—	—	1	24
122	0910	080	24	22	25	30	0200	150	036	—	—	1	03
123	0900	072	24	23	22	26	0089	080	072	—	—	1	05
124	0900	066	24	24	21	27	0106	086	084	—	—	1	09
125	0920	060	25	22	23	30	0275	150	228	—	—	1	28
126	0920	056	25	24	23	28	0145	125	070	—	—	1	06
127	0760	277	18	17	17	31	0264	129	132	—	—	1	32

Little Pap (NO 265844)

128	0820	100	18	17	17	28	0426	162	042	—	—	1	08
129	0820	102	17	21	16	31	0531	134	067	—	—	1	17
130	0820	106	19	20	16	24	0296	122	063	—	—	1	09
131	0830	106	20	19	18	32	0356	217	073	—	—	1	18
132	0850	108	20	17	13	32	0117	071	036	—	—	1	12
133	0850	122	17	22	14	30	0323	102	054	—	—	1	15
134	0850	184	18	12	16	26	0294	113	062	—	—	1	11
135	0940	208	18	21	09	26	0115	085	074	—	—	1	22
136	0960	208	18	21	21	24	0205	092	054	—	—	1	03
137	0930	200	18	27	24	31	0364	114	061	—	—	1	07
138	0930	196	18	15	18	31	0632	131	043	—	—	1	10
139	0920	190	18	22	13	29	0466	085	048	—	—	1	13
140	0920	192	18	18	12	34	0481	108	044	—	—	1	17
141	0970	184	18	16	09	18	0180	151	032	—	—	1	05
142	0960	186	18	15	09	18	0075	097	064	—	—	1	10

Conachcraig (NO 284872)

143	0840	208	11	17	12	25	0379	146	054	—	—	1	12
144	0840	215	11	20	12	28	0293	142	038	—	—	1	11
145	0840	220	11	15	10	26	0356	191	064	—	—	1	18
146	0840	236	11	11	08	15	0119	139	045	—	—	1	06
147	0850	216	11	10	05	22	0112	158	038	—	—	1	11
148	0650	286	17	17	13	45	0498	195	038	—	—	1	20
149	0640	286	17	14	13	28	0074	231	061	—	—	1	16
150	0650	302	19	11	10	21	0168	179	103	—	—	1	20
151	0640	312	20	14	10	19	0172	131	091	—	—	1	14
152	0640	310	20	15	11	18	0173	122	071	—	—	1	09

153	0660	292	16	14	14	26	0223	168	049	---	---	1	10
154	0660	292	16	09	13	23	0365	214	061	---	---	1	11

Cac Carn Mor (NO 245857)

155	1050	226	10	09	05	17	0476	173	051	118	277	1	11
156	1070	176	14	16	13	23	0416	193	074	053	101	1	13
157	1080	216	16	15	15	20	0341	093	149	084	111	1	13
158	1080	220	15	16	16	22	0408	154	109	240	206	1	11
159	1080	222	17	20	16	20	0424	176	152	205	296	1	11
160	1090	236	18	21	13	24	0586	177	097	475	262	1	19
161	1070	234	21	25	18	31	0340	259	260	270	270	1	59
162	1100	276	28	27	26	32	0586	124	109	296	124	1	11

Summit Col (NO 244858)

163	1030	256	31	31	30	35	0333	223	154	263	234	1	13
164	1030	258	33	36	32	36	0418	227	284	317	179	1	20
165	1040	258	34	33	36	44	0472	166	165	266	240	1	23
166	1050	258	34	24	28	35	0283	190	075	283	064	1	09
167	1070	254	34	25	28	31	0437	189	083	229	188	1	04
168	1080	250	28	26	26	30	0231	152	094	093	139	1	07
169	1090	252	28	22	29	32	0495	106	111	374	035	1	06
170	1100	248	28	25	23	31	0440	275	094	440	142	1	13
171	1080	244	28	23	26	32	0392	204	103	244	178	1	11
172	1110	272	28	26	26	33	0763	300	136	763	250	1	17

White Mounth (NO 237840)

173	1040	058	19	18	22	25	0352	103	114	245	235	1	06
174	1020	184	12	14	11	22	0686	182	126	181	084	1	24
175	1020	180	12	16	11	30	0832	195	104	139	101	1	34
176	1040	184	14	11	10	27	1451	148	071	143	079	1	21
177	1030	184	12	12	17	22	0545	200	103	178	069	1	09
178	1020	184	12	17	11	31	0140	211	084	206	179	1	29
179	1020	168	13	10	11	25	0372	174	060	137	148	1	15
180	1020	186	10	09	09	22	0405	151	044	026	075	1	10
181	1040	182	10	10	09	23	0681	132	064	061	103	1	16
182	1040	186	10	10	10	25	0625	167	058	163	085	1	15
183	1000	226	23	19	20	26	0588	333	122	144	243	1	13

Eagle Ridge (NO 247854)

184	1020	190	15	16	12	24	0361	198	073	126	081	1	15
185	1030	172	15	17	14	33	0726	332	086	129	399	1	28
186	1030	144	16	16	13	27	0489	159	096	130	174	1	23
187	1030	166	16	15	18	24	0752	251	163	236	114	1	17
188	1020	164	17	19	16	31	0249	161	111	099	121	1	29
189	1020	158	17	22	19	27	0175	157	092	081	175	1	13
190	1040	158	18	19	18	30	0588	211	103	300	142	1	21
191	1040	160	20	20	17	32	0207	156	090	123	241	1	23
192	1040	162	19	24	17	32	0589	218	140	183	285	1	36
193	1040	164	18	21	18	30	0700	154	088	204	292	1	18
194	1060	162	17	19	15	27	0471	203	116	212	164	1	24
195	1070	170	18	22	19	27	0396	325	138	220	092	1	19
196	1080	168	16	19	17	28	0410	234	163	120	254	1	31
197	1090	166	16	20	16	23	0297	152	108	259	154	1	13
198	1050	240	20	17	17	24	0438	151	128	108	099	1	16
199	1050	228	21	22	20	24	0296	163	167	142	296	1	12
200	1060	250	21	18	24	28	0265	124	112	174	052	1	08

2. Mount Keen

Gathering Cairn (NO 424885)

201	0640	310	22	28	20	34	0404	167	116	225	301	1	28
202	0640	306	23	28	20	32	0562	184	114	312	263	1	24
203	0640	298	23	25	21	32	0429	186	165	228	186	1	32
204	0650	314	23	24	23	33	0361	159	176	185	205	1	31
205	0660	320	24	25	24	31	0271	139	108	165	148	1	13
206	0710	280	22	27	21	23	0244	162	156	228	120	1	05
207	0710	288	21	24	21	23	0397	160	104	156	322	1	04
208	0710	296	23	25	21	31	0474	199	082	413	184	1	14
209	0700	288	22	17	19	21	0199	176	096	190	165	1	03
210	0740	306	18	16	15	33	0353	125	061	183	077	1	19
211	0740	300	17	12	15	27	0352	131	055	155	251	1	11
212	0740	294	19	18	16	26	0345	127	129	122	067	1	22
213	0730	290	18	17	14	29	0275	109	055	104	159	1	14
214	0750	304	13	16	10	26	0609	285	143	231	113	1	39
215	0750	314	12	10	11	24	0489	196	095	163	040	1	21

216	0770	278	13	15	11	21	0530	232	097	495	238	1	17
217	0770	312	14	16	12	32	0360	201	063	185	223	1	22
218	0780	310	13	14	09	26	0729	224	058	236	153	1	17
219	0780	314	13	09	11	24	0238	131	101	146	128	1	23
220	0710	290	19	21	16	26	0108	071	173	108	057	1	30
221	0710	286	18	20	16	27	0141	095	087	081	141	1	17
222	0710	288	18	19	16	26	0211	163	122	157	140	1	21
223	0720	292	18	11	15	31	0227	125	092	056	064	1	25
224	0720	274	18	15	17	27	0621	197	201	153	093	1	35
225	0730	270	17	14	12	31	0389	133	045	143	033	1	15
226	0730	268	17	15	11	32	0456	232	055	137	160	1	20
227	0740	280	16	20	14	34	0742	108	046	236	136	1	16
228	0740	278	15	16	13	25	0318	116	067	133	286	1	14
229	0740	268	17	13	11	22	0352	174	139	070	162	1	27
230	0740	266	18	22	10	21	0451	141	172	124	157	1	33
231	0750	318	19	23	21	25	0416	221	115	256	285	1	08
232	0750	322	20	22	22	33	0643	208	099	249	118	1	19
233	0750	324	20	21	22	30	0594	164	113	124	311	1	16
234	0760	328	20	25	21	27	0660	175	098	261	151	1	10
235	0770	322	21	22	22	35	0419	203	104	238	216	1	23
236	0770	316	22	21	22	33	0442	227	117	298	254	1	22
237	0770	332	23	21	22	30	0738	289	086	284	226	1	12
238	0780	316	22	23	23	28	0440	155	094	128	099	1	08
239	0780	324	22	25	23	29	0865	187	102	222	329	1	11
240	0750	336	20	22	21	29	0269	187	096	269	269	1	13
241	0640	310	20	21	22	36	0531	171	064	182	378	1	16
242	0640	312	20	20	22	29	0701	202	077	701	248	1	09
243	0640	312	21	22	22	29	0861	214	060	443	252	1	07
244	0650	308	21	23	21	28	0904	168	051	458	487	1	06
245	0660	308	22	23	23	26	0578	155	098	386	268	1	05
246	0670	312	23	22	20	28	0379	206	069	262	110	1	10
247	0680	312	23	22	22	32	0337	176	095	336	334	1	17
248	0760	308	21	17	20	34	0262	173	168	102	021	1	41
249	0750	306	20	21	20	28	0491	254	078	278	171	1	12
250	0770	306	20	19	21	33	0220	178	065	168	154	1	14
251	0760	090	15	15	13	27	0152	143	044	091	047	1	11
252	0760	092	15	14	14	21	0224	140	043	061	099	1	05

253	0770	098	12	12	10	23	0298	079	026	106	073	1	06
254	0770	110	12	11	12	26	0493	181	045	172	204	1	11
255	0750	102	17	16	17	29	0539	160	036	069	128	1	08
256	0740	108	16	15	11	40	0743	148	046	119	092	1	22
257	0740	104	18	21	18	29	0682	177	052	200	288	1	10
258	0740	100	18	23	17	30	0264	130	059	163	132	1	13
259	0740	094	20	24	18	30	0648	089	100	036	174	1	21
260	0740	098	18	17	16	30	0511	189	155	116	033	1	38
261	0740	320	20	18	14	28	0681	120	057	242	104	1	14
262	0750	324	21	20	22	26	0298	155	066	275	204	1	05
263	0750	328	22	21	18	29	0546	145	060	284	119	1	11
264	0750	336	22	24	13	28	0535	131	024	300	199	1	06
265	0740	328	22	23	21	30	0206	131	059	224	409	1	09

Braid Cairn (NO 426873)

266	0740	346	22	23	21	27	0482	145	104	214	155	1	11
267	0740	348	22	22	21	26	0144	209	076	200	210	1	07
268	0770	348	22	17	20	31	0354	137	049	124	229	1	09
269	0770	352	22	21	17	34	0341	081	040	218	076	1	12
270	0770	340	22	24	16	30	0345	103	080	098	131	1	19
271	0770	338	21	22	14	29	0236	101	170	114	105	1	44
272	0760	356	17	17	13	27	0202	081	042	064	098	1	10
273	0760	036	15	13	15	18	0246	173	056	053	091	1	03
274	0780	022	14	16	12	27	0210	090	036	038	079	1	09
275	0780	020	16	17	12	32	0260	107	031	100	156	1	11
276	0780	278	18	16	15	18	0239	084	056	083	125	1	03
277	0770	288	18	13	17	27	0350	198	156	257	133	1	27
278	0770	300	18	18	16	24	0300	113	102	320	208	1	14
279	0770	254	17	20	12	15	0415	153	153	280	232	1	08
280	0770	258	17	19	19	33	0113	061	038	108	036	1	09
281	0770	260	17	18	12	27	0477	167	045	240	151	1	12
282	0790	288	18	18	15	31	0420	099	038	108	171	1	11
283	0800	304	18	15	14	32	0370	136	053	178	105	1	16
284	0800	298	18	17	14	28	0341	131	070	140	198	1	17
285	0810	286	18	17	15	25	0334	112	130	105	069	1	23

Mount Keen (NO 409869)

286	0850	336	20	19	16	29	0511	211	089	271	182	1	20

287	0860	036	22	22	19	32	0379	184	065	082	117	1	15
288	0870	054	21	20	17	34	0386	173	112	262	303	1	33
289	0880	060	22	25	17	35	0414	232	076	129	208	1	24
290	0900	078	22	16	17	28	0145	138	104	145	072	1	20
291	0890	094	22	20	21	29	0260	102	059	260	135	1	08
292	0890	106	22	22	20	31	0280	098	074	237	053	1	14
293	0890	094	22	22	17	31	0198	200	067	270	101	1	16
294	0880	108	24	29	19	34	0390	089	052	343	132	1	14
295	0890	114	22	23	18	34	0358	189	150	173	448	1	41
296	0890	118	22	28	20	31	0396	147	064	191	110	1	12
297	0890	122	22	28	20	34	0418	180	063	147	225	1	15
298	0880	146	22	23	17	29	0152	100	095	128	105	1	20
299	0880	124	22	22	18	27	0205	111	097	064	148	1	15
300	0890	138	22	22	23	25	0281	135	076	194	139	1	03

<u>Metamorphic Sample</u>

Carn Aosda (NO 134792)

301	0890	112	23	25	17	29	0087	064	022	043	087	2	05
302	0890	110	23	24	16	31	0053	046	025	031	053	2	07
303	0900	154	21	21	16	29	0202	050	040	042	073	2	09
304	0900	150	21	15	18	29	0303	046	070	182	124	2	13
305	0890	152	20	22	18	25	0140	083	065	140	034	2	08
306	0890	154	20	21	16	27	0159	062	047	074	159	2	09
307	0890	134	20	22	20	25	0161	080	029	052	113	2	03

Carn Chrionaidh (NO 133805)

308	0640	096	18	24	18	37	0087	083	032	059	052	2	10
309	0650	100	18	22	20	33	0181	054	018	110	024	2	04
310	0660	108	18	21	19	33	0094	078	027	053	032	2	07
311	0670	106	18	22	21	30	0108	066	045	023	030	2	07
312	0670	110	19	23	24	29	0187	087	022	122	079	2	02
313	0670	112	19	20	24	33	0113	074	018	072	034	2	03
314	0680	106	19	22	20	37	0150	055	011	032	018	2	03
315	0690	102	19	23	22	42	0044	046	006	072	020	2	02
316	0710	108	20	21	22	37	0066	065	017	043	015	2	04
317	0710	110	20	19	23	33	0147	081	023	202	031	2	04

318	0720	116	20	24	23	38	0072	097	021	064	047	2	05
319	0720	120	21	25	24	35	0136	069	019	110	040	2	04
320	0730	104	22	24	26	41	0097	082	014	132	051	2	04
321	0580	074	31	32	34	47	0096	066	020	095	081	2	05
322	0610	064	32	32	31	53	0166	064	013	118	091	2	05
323	0620	060	33	25	26	39	0095	057	021	089	051	2	05
324	0660	058	33	18	25	45	0123	060	011	072	027	2	04
325	0700	052	32	21	22	34	0087	041	012	140	078	2	03
326	0690	048	31	29	31	46	0101	067	014	086	021	2	04
327	0690	056	32	27	26	54	0099	072	016	091	036	2	08
328	0700	054	32	26	27	36	0073	043	024	089	040	2	04
329	0690	044	31	26	30	41	0136	051	021	026	035	2	04
330	0690	040	30	25	29	46	0081	045	017	028	046	2	05
331	0710	032	25	22	25	31	0118	040	026	029	043	2	03
332	0720	300	27	18	24	37	0168	046	017	016	009	2	04
333	0710	316	25	24	19	29	0083	039	035	067	027	2	06
334	0710	310	26	22	23	34	0086	060	024	028	042	2	05
335	0700	306	26	23	20	33	0164	053	032	036	060	2	07
336	0690	308	27	23	19	39	0146	073	018	054	035	2	06
337	0710	312	25	18	20	29	0075	065	032	092	024	2	05

Creag nan Gabhar (NO 154841)

338	0630	192	30	29	29	43	0192	060	012	116	050	2	03
339	0650	174	26	27	30	35	0093	057	019	104	042	2	02
340	0670	186	26	19	11	27	0213	071	018	118	129	2	05
341	0670	178	26	18	12	22	0192	066	025	058	074	2	04
342	0690	194	25	24	12	28	0161	039	024	064	050	2	07
343	0710	198	25	23	15	32	0121	054	020	059	093	2	06
344	0700	176	25	26	15	30	0372	088	032	149	097	2	08
345	0690	168	24	21	18	24	0206	048	024	083	026	2	03
346	0720	172	24	25	18	30	0171	055	039	069	097	2	08
347	0730	164	24	22	11	31	0175	073	033	050	090	2	11
348	0740	160	23	19	20	28	0116	104	044	062	114	2	06
349	0740	156	23	16	19	27	0137	074	057	031	056	2	08
350	0750	150	22	22	20	27	0257	071	064	047	086	2	08

APPENDIX 11

Boulder Terrace Field Measurements

Key to the Columns:

A. Number

B. Altitude (metres above sea-level)

C. Slope Aspect (degrees magnetic)

D. Slope Angle (degrees from the horizontal)

E. Angle of the ground below the riser

F. Angle of the terrace surface - normal to the riser

G. Angle of the terrace surface - parallel to the riser

H. Angle of the riser

I. Length of the terrace - normal to the riser (tenths of a metre)

J. Length of the terrace - parallel to the riser (tenths of a metre)

K. Length of the riser (tenths of a metre)

L. Orientation of the riser (degrees magnetic)

M. Thickness of the terrace-layer (tenths of a metre)

Granite Sample

Coire na Ciche (NO 270868)

A	B	C	D	E	F	G	H	I	J	K	L	M
001	0650	281	19	18	22	02	32	195	224	053	016	13

Meall ah Tionail (NO 223880)

A	B	C	D	E	F	G	H	I	J	K	L	M
002	0740	279	21	25	26	03	30	106	441	076	007	07
003	0740	303	20	19	08	03	26	475	437	160	032	20
004	0740	318	19	06	10	06	29	074	367	073	037	29
005	0750	324	19	06	07	04	31	120	192	066	052	28
006	0750	331	19	06	10	03	34	109	363	067	048	31
007	0750	332	19	08	08	04	26	166	246	057	230	18
008	0760	314	20	03	06	03	28	151	187	043	048	18
009	0760	332	19	15	08	05	27	109	188	052	058	11
010	0760	327	21	08	08	03	26	110	125	044	230	14
011	0740	286	18	23	15	02	33	194	143	056	010	10
012	0750	326	20	09	07	02	23	071	241	029	043	07
013	0750	330	20	08	08	05	29	075	334	122	238	44
014	0750	328	19	16	09	02	30	072	249	098	232	24

015	0760	326	19	06	07	03	31	050	153	062	043	26
016	0740	346	22	19	11	02	32	199	374	142	238	32
017	0760	006	22	20	17	04	23	211	178	056	272	03
018	0760	008	22	18	16	02	32	142	158	067	112	16
019	0760	006	22	14	16	06	28	100	233	101	106	24
020	0760	321	20	13	12	07	27	265	233	125	056	30
021	0770	348	19	16	12	10	27	081	205	078	068	15
022	0770	341	19	18	13	09	27	073	154	035	237	05
023	0770	338	19	15	16	08	27	050	217	054	050	11
024	0770	359	21	14	17	12	28	140	321	032	238	08
025	0760	326	20	17	15	06	29	091	274	074	067	15
026	0750	098	21	20	23	04	32	064	238	060	186	12

Meikle Pap (NO 260860)

027	0890	290	17	13	09	05	30	476	990	167	024	49

Gathering Cairn (NO 424885)

028	0750	298	14	12	09	05	24	372	437	133	214	28
029	0730	248	17	14	16	04	33	980	614	071	346	23

APPENDIX 111

Gliding Boulder Field Measurements

Key to the columns:

A. Number
B. Altitude (metres above sea-level)
C. Slope aspect (degrees magnetic)
D. Slope angle (degrees from the horizontal)
E. Primary furrow length (centimetres)
F. Secondary furrow length (centimetres)
G. Boulder length (centimetres)
H. Boulder width (centimetres)
I. Boulder height (centimetres)
J. Boulder shape 1-rectangular prismatic 2-irregular
K. Orientation of the boulder long axis (degrees magnetic)
L. Deviation of the boulder long axis (calculated from C and K)
M. Bow-wave height (centimetres)
N. Bow-wave length (centimetres)
O. Lithology 1-granite 2-metamorphic

Metamorphic Sample

Allt a Gharbh-choire (NO 163800)

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
001	0750	078	22	055	000	080	064	037	1	004	74	18	17	2
002	0750	060	22	048	000	074	047	024	1	052	08	24	25	2
003	0750	046	22	033	000	081	053	032	2	042	04	18	26	2
004	0750	048	22	030	000	063	050	024	1	016	32	15	23	2
005	0750	050	23	028	000	058	035	010	2	048	02	16	28	2
006	0740	063	23	042	000	099	061	027	1	090	27	20	18	2
007	0740	064	22	031	000	055	042	016	2	056	08	19	26	2
008	0730	064	25	066	000	072	052	033	1	058	06	42	24	2
009	0730	062	26	113	000	065	054	021	1	064	02	29	38	2
010	0730	028	24	124	000	081	043	016	2	014	14	17	29	2
011	0720	042	30	065	000	053	050	025	2	046	04	30	26	2
012	0720	046	28	084	000	100	043	021	1	058	12	13	18	2
013	0720	044	28	065	000	060	043	019	2	334	70	33	19	2
014	0720	044	28	086	000	088	055	034	1	084	40	14	18	2

015	0710	042	28	032	000	064	027	021	2	304	82	36	28	2
016	0710	032	20	196	000	082	037	021	1	036	04	25	32	2
017	0710	044	20	030	000	063	038	022	2	074	30	17	32	2
018	0700	052	20	026	000	059	036	017	2	084	32	18	20	2
019	0700	032	24	043	000	064	047	034	2	360	32	21	29	2
020	0700	026	22	036	000	038	022	016	1	100	74	31	22	2
021	0760	190	21	050	000	098	064	031	1	228	38	10	12	2
022	0760	212	21	034	000	162	150	044	2	222	10	22	12	2
023	0800	172	24	100	000	078	054	036	2	178	06	00	00	2
024	0800	182	24	021	000	063	040	019	1	298	64	08	10	2
025	0860	280	22	031	000	056	039	022	2	282	02	12	16	2
026	0860	298	21	040	000	092	061	022	1	304	06	25	34	2
027	0860	290	19	045	000	114	064	038	1	296	06	13	21	2
028	0840	290	19	025	000	093	054	024	1	286	04	23	35	2
029	0840	316	17	062	000	134	038	029	2	302	14	07	22	2
030	0820	318	16	052	000	092	069	029	1	316	02	00	00	2
031	0820	310	14	059	000	122	065	035	2	314	04	14	30	2
032	0810	316	12	033	000	058	044	029	2	240	76	22	39	2
033	0810	306	14	020	000	081	030	016	1	024	78	13	41	2
034	0800	324	15	026	000	156	072	022	1	312	12	11	89	2
035	0800	336	14	015	000	063	026	018	2	350	14	16	14	2
036	0790	328	16	029	000	085	055	038	2	360	32	20	25	2
037	0790	356	18	042	000	109	102	043	1	048	52	22	63	2
038	0780	324	15	023	000	082	027	033	2	046	82	06	20	2
039	0780	338	19	046	000	117	089	052	1	030	52	32	80	2
040	0760	328	17	031	000	051	022	022	2	302	26	19	50	2
041	0840	324	25	063	181	086	072	045	1	308	16	13	12	2
042	0850	326	28	042	068	120	077	027	1	312	14	16	15	2
043	0850	326	28	041	000	098	056	042	2	058	88	26	46	2
044	0850	326	27	052	062	039	026	017	1	328	02	09	04	2
045	0880	294	25	056	082	109	048	036	2	284	10	14	29	2
046	0880	308	21	048	000	118	061	028	1	302	06	21	25	2
047	0880	314	21	096	000	110	082	023	1	020	66	20	24	2
048	0890	320	30	081	181	145	051	026	1	316	04	20	70	2
049	0900	316	29	065	190	092	065	027	1	228	88	15	35	2
050	0900	326	29	050	094	052	047	022	1	044	78	15	22	2
051	0890	326	29	051	111	100	087	025	2	274	52	20	34	2

052	0890	325	28	040	038	073	046	026	1	345	20	15	14	2
053	0900	306	25	039	045	079	043	023	2	318	12	28	26	2
054	0900	320	22	043	000	079	054	017	2	316	04	15	12	2
055	0910	338	28	065	091	061	034	021	1	006	28	31	40	2
056	0910	318	22	091	062	081	066	042	2	332	14	35	43	2
057	0920	332	22	033	094	082	068	023	2	346	14	26	72	2
058	0920	320	29	053	110	091	051	034	2	328	08	39	56	2
059	0930	318	31	075	242	083	052	016	2	318	00	42	14	2
060	0930	350	19	035	039	058	081	026	2	256	86	22	62	2
061	0770	028	23	054	093	105	034	021	2	036	08	39	06	2
062	0780	060	19	044	122	106	082	050	1	066	06	12	16	2
063	0800	022	14	058	027	147	084	069	2	340	44	38	51	2
064	0810	020	16	062	000	113	092	026	1	322	68	37	75	2
065	0810	344	17	059	000	101	070	054	2	340	04	26	52	2
066	0820	004	22	084	000	095	055	031	1	016	12	43	34	2
067	0830	352	29	112	000	103	075	045	1	080	86	46	19	2
068	0820	302	28	081	000	079	052	032	1	300	02	47	20	2
069	0810	316	26	061	000	064	058	017	1	338	22	50	29	2
070	0810	298	19	056	000	068	065	044	2	278	20	36	37	2

Allt Coire Fionn (NO 157786)

071	0660	340	37	082	000	119	079	035	2	346	06	42	13	2
072	0660	354	36	079	000	077	064	034	1	004	10	83	42	2
073	0660	348	37	093	036	047	032	025	1	006	18	37	26	2
074	0670	044	29	069	091	059	044	039	2	140	84	30	06	2
075	0670	042	28	108	153	137	065	063	1	046	04	39	12	2
076	0700	060	22	140	000	127	080	023	1	062	02	35	11	2
077	0700	062	23	056	017	044	034	031	2	002	60	27	58	2
078	0710	056	22	038	000	135	082	035	2	048	08	20	34	2
079	0720	046	21	071	000	093	043	046	1	132	86	30	26	2
080	0710	068	25	042	000	088	070	058	2	076	08	31	27	2
081	0710	072	25	053	000	071	049	043	1	138	66	49	21	2
082	0710	082	27	057	078	079	069	022	2	084	02	28	12	2
083	0720	076	21	066	045	215	035	058	2	072	04	34	21	2
084	0770	110	22	037	040	074	046	019	1	006	76	16	10	2
085	0770	104	21	043	138	090	069	032	1	092	12	26	18	2
086	0680	226	28	043	000	192	112	063	1	326	80	16	11	2

087	0680	214	26	035	065	060	054	039	1	234	20	28	24	2
088	0680	212	31	047	101	045	028	026	1	198	14	10	10	2
089	0690	222	23	034	049	059	050	015	1	286	64	48	14	2
090	0700	230	23	045	000	122	062	034	1	222	08	31	13	2
091	0700	238	22	052	000	183	042	016	1	248	10	13	37	2
092	0710	284	27	031	152	065	063	036	2	312	28	20	07	2
093	0710	290	24	042	179	123	052	043	2	300	10	29	11	2
094	0730	262	19	054	000	132	067	032	1	276	14	16	12	2
095	0750	210	24	030	111	056	041	020	1	218	08	16	10	2
096	0770	188	21	058	000	090	042	013	2	180	08	11	14	2
097	0780	338	22	137	000	080	052	036	2	354	16	29	15	2
098	0790	312	21	062	083	094	063	038	1	320	14	13	29	2
099	0780	328	23	033	046	051	032	025	2	330	02	26	42	2
100	0770	296	23	120	119	078	030	018	1	306	10	28	11	2

Allt a Ghlinne Bhig (NO 150755)

101	0550	158	23	062	000	063	040	030	2	198	40	00	00	2
102	0560	164	23	027	071	103	066	045	1	162	02	00	00	2
103	0560	170	18	019	052	083	040	016	1	186	16	00	00	2
104	0570	120	22	060	062	092	082	028	2	122	02	00	00	2
105	0580	086	38	093	066	059	050	026	2	174	88	00	00	2
106	0600	118	18	070	000	093	072	035	2	188	70	00	00	2
107	0600	106	14	024	000	056	042	027	2	188	82	35	45	2
108	0620	104	14	020	046	064	032	025	2	128	24	00	00	2
109	0640	094	15	023	000	098	052	022	1	086	08	00	00	2
110	0630	130	15	041	000	082	080	041	2	138	08	00	00	2
111	0650	118	18	020	000	087	044	036	2	114	04	00	00	2
112	0660	094	19	037	000	056	030	014	2	080	14	00	00	2
113	0660	114	26	062	110	063	045	020	2	130	16	22	13	2
114	0690	116	26	065	000	058	036	024	1	140	24	24	16	2
115	0690	112	26	047	000	063	033	012	2	126	14	00	00	2
116	0700	130	28	048	000	039	030	013	1	160	30	12	14	2
117	0710	284	28	032	056	140	072	046	2	246	38	46	51	2
118	0700	238	18	070	000	120	086	035	1	224	14	20	18	2
119	0700	240	13	044	000	079	068	029	2	248	08	10	24	2
120	0690	254	13	030	000	068	022	015	2	274	20	00	00	2
121	0680	280	12	147	000	079	048	016	1	268	12	00	00	2
122	0670	268	19	129	000	080	058	028	2	258	10	00	00	2

123	0650	244	17	025	000	079	053	029	1	316	72	21	28	2
124	0650	258	17	042	000	082	056	028	1	348	90	00	00	2
125	0640	282	18	044	000	042	041	027	2	212	70	00	00	2
126	0640	268	18	034	000	062	030	019	1	276	08	30	23	2
127	0650	312	18	045	000	055	050	049	2	188	56	00	00	2
128	0640	268	18	024	000	053	031	018	1	284	16	00	00	2
129	0630	276	18	019	000	058	036	023	2	360	84	00	00	2
130	0640	252	18	028	000	093	077	025	2	242	10	14	25	2
131	0650	202	19	088	000	068	037	019	1	214	12	00	00	2
132	0620	314	17	020	032	058	033	021	1	050	84	00	00	2
133	0600	296	18	026	080	085	051	025	2	300	04	00	00	2
134	0580	290	16	027	000	054	038	032	1	210	80	00	00	2
135	0590	022	31	035	088	069	040	035	2	016	06	34	26	2
136	0570	024	30	069	000	130	050	032	1	038	14	20	12	2
137	0570	010	29	023	092	080	047	025	1	340	30	26	16	2
138	0550	018	27	020	000	060	032	022	1	052	34	00	00	2
139	0540	010	25	095	000	082	058	018	1	034	24	30	11	2
140	0530	024	24	063	000	113	092	062	1	320	64	48	55	2

Allt a Choire Dhirich (NO 130765)

141	0500	078	31	042	062	054	033	032	2	088	10	23	19	2
142	0510	120	26	048	000	056	034	019	2	142	22	00	00	2
143	0520	094	22	055	000	065	027	023	1	116	22	00	00	2
144	0540	112	25	033	000	089	047	028	1	144	32	00	00	2
145	0560	110	25	023	000	076	054	039	1	104	06	00	00	2
146	0560	074	23	031	000	055	035	012	1	106	32	00	00	2
147	0550	180	30	026	000	058	045	031	1	172	08	00	00	2
148	0550	002	26	038	000	045	038	020	1	016	14	00	00	2
149	0560	066	18	031	000	138	119	042	1	060	06	00	00	2
150	0570	076	18	077	000	085	062	055	1	082	06	00	00	2
151	0580	060	18	058	000	088	042	021	2	072	12	00	00	2
152	0580	054	19	029	000	057	036	012	2	074	20	16	12	2
153	0590	090	17	034	000	040	022	013	1	106	16	00	00	2
154	0600	096	17	076	000	046	020	016	1	104	08	00	00	2
155	0600	108	18	025	000	065	048	018	1	026	82	00	00	2
156	0610	056	18	059	000	049	021	009	2	064	08	00	00	2
157	0630	064	25	057	000	074	039	018	1	092	28	00	00	2

157	0630	064	25	057	000	074	039	018	1	092	28	00	00	2
158	0620	068	25	036	000	054	034	023	1	088	20	00	00	2
159	0610	066	25	039	000	053	031	019	1	094	28	00	00	2
160	0610	058	16	038	049	050	030	028	2	358	60	00	00	2
161	0620	084	17	043	000	044	035	024	2	058	26	00	00	2
162	0630	088	16	035	000	076	047	033	2	068	20	00	00	2
163	0630	090	16	041	000	079	056	024	1	122	32	00	00	2
164	0670	088	17	040	000	059	037	021	1	106	18	14	22	2
165	0670	072	17	038	022	123	062	026	2	118	46	06	09	2
166	0630	076	15	034	000	063	047	020	2	124	48	00	00	2
167	0620	090	16	050	000	124	087	029	2	082	08	22	15	2
168	0620	086	16	065	000	055	033	031	2	150	64	00	00	2
169	0610	098	17	082	000	066	064	022	1	032	66	00	00	2
170	0610	248	15	020	000	050	042	015	1	282	34	00	00	2
171	0620	246	15	030	000	056	027	016	2	284	38	00	00	2
172	0600	260	16	029	000	093	064	036	1	182	78	00	00	2
173	0580	242	17	059	000	075	054	042	1	262	20	21	12	2
174	0580	240	17	035	000	092	058	029	1	220	20	20	21	2
175	0570	250	18	049	000	084	072	019	2	260	10	00	00	2
176	0560	238	17	017	000	082	044	024	1	296	58	00	00	2
177	0550	234	18	052	000	056	033	020	1	236	02	00	00	2
178	0550	230	17	034	000	061	036	028	1	222	08	00	00	2
179	0540	214	19	026	000	148	076	042	2	300	86	00	00	2
180	0520	204	19	024	000	074	069	052	1	210	06	00	00	2

Allt Coolah (NO 124744)

181	0450	070	11	026	070	104	047	033	1	078	08	11	15	2
182	0460	088	14	044	000	063	043	035	2	064	24	24	22	2
183	0480	078	14	057	000	086	049	016	1	090	12	10	26	2
184	0480	052	18	027	000	080	054	023	1	058	06	00	00	2
185	0510	082	18	018	000	131	057	022	2	100	18	18	31	2
186	0520	108	27	024	000	083	048	024	1	138	30	00	00	2
187	0550	124	27	021	000	052	037	018	1	136	12	00	00	2
188	0560	100	26	029	000	042	038	015	1	042	58	09	13	2
189	0620	074	28	021	000	089	042	021	1	072	02	00	00	2
190	0630	086	28	042	000	052	030	017	1	090	04	00	00	2
191	0640	080	33	038	000	059	033	021	2	110	30	00	00	2

192	0620	132	21	028	000	082	066	038	2	154	22	12	14	2
193	0560	246	22	030	000	135	085	063	2	210	36	00	00	2
194	0560	240	13	026	000	160	062	031	2	230	10	00	00	2
195	0570	292	13	052	000	081	034	014	1	286	06	00	00	2
196	0560	278	13	035	000	098	047	026	1	282	04	00	00	2
197	0540	262	14	039	000	050	036	035	1	278	16	00	00	2
198	0540	274	14	086	000	059	040	033	2	286	12	11	09	2
199	0530	282	12	068	000	090	057	014	2	280	02	15	12	2
200	0510	236	12	062	000	077	043	017	2	244	08	10	07	2

GRANITE SAMPLE

Stuic Corrie (NO 230855)

201	0900	148	19	041	000	152	091	058	2	144	04	16	00	1
202	0900	142	19	030	000	172	057	044	2	222	80	16	00	1
203	0900	138	19	031	066	096	087	036	1	182	44	03	00	1
204	0900	142	19	013	000	077	032	026	1	128	14	02	00	1
205	0900	136	19	056	000	172	162	055	1	104	32	00	00	1
206	0900	136	19	026	034	077	050	023	1	154	18	00	00	1
207	0900	136	20	087	000	122	080	048	1	116	20	53	52	1
208	0900	134	19	038	000	094	045	039	2	114	20	17	00	1
209	0900	138	19	047	000	124	066	043	2	236	82	19	00	1
210	0900	134	20	073	000	058	054	027	1	190	56	00	00	1
211	0890	132	20	093	000	083	066	039	1	188	56	37	34	1
212	0890	126	21	029	142	082	043	037	2	116	10	18	14	1
213	0890	122	20	085	000	081	048	039	2	186	64	16	23	1
214	0890	128	12	137	000	117	125	089	2	196	68	00	00	1
215	0890	134	16	183	000	133	081	074	2	166	32	00	00	1
216	0880	142	16	046	074	097	076	028	2	150	08	00	00	1
217	0880	128	16	042	000	208	132	076	2	132	04	34	42	1
218	0880	128	16	147	232	194	078	075	2	130	02	54	65	1
219	0880	118	13	083	000	126	099	046	2	168	50	00	00	1
220	0880	100	09	042	000	236	193	055	2	150	50	00	00	1
221	0880	094	09	084	000	220	098	079	1	068	26	00	00	1
222	0870	020	11	102	000	198	079	059	1	022	02	00	00	1
223	0870	008	13	040	036	167	109	056	2	038	30	00	00	1
224	0870	306	18	231	000	142	064	031	2	308	02	00	00	1

225	0870	320	20	069	105	053	024	016	2	338	18	00	00	1
226	0860	316	20	085	000	090	055	042	1	340	24	00	00	1
227	0860	304	21	240	000	172	095	079	1	300	04	00	00	1
228	0860	320	20	073	000	206	070	040	1	322	02	00	00	1
229	0860	296	22	087	000	111	050	041	1	300	04	00	00	1
230	0860	278	23	086	000	091	049	028	2	282	04	00	00	1
231	0860	272	23	041	087	088	043	041	2	298	26	23	21	1
232	0860	300	22	097	000	042	028	022	1	320	20	00	00	1
233	0850	284	22	124	000	124	095	054	1	288	04	00	00	1
234	0850	288	21	106	000	064	043	041	2	338	50	00	00	1
235	0850	298	21	072	000	088	069	041	2	288	10	00	00	1
236	0850	282	21	106	135	193	059	049	2	290	08	22	25	1
237	0850	292	21	032	000	074	062	042	1	266	26	00	00	1
238	0850	321	20	122	000	102	098	028	2	280	41	00	00	1
239	0840	308	20	085	000	082	059	037	1	245	63	00	00	1
240	0840	334	16	186	000	163	082	069	2	356	22	00	00	1
241	0840	326	16	100	000	156	092	056	1	328	02	00	00	1
242	0840	340	17	153	098	153	069	063	2	356	16	00	00	1
243	0840	332	17	113	035	209	093	060	1	336	04	00	00	1
244	0840	336	17	098	000	139	059	041	2	008	32	00	00	1
245	0840	338	16	080	330	216	193	087	1	340	02	00	00	1
246	0850	320	16	119	000	115	094	023	2	316	04	36	37	1
247	0850	328	16	032	067	126	112	045	2	002	34	00	00	1
248	0850	326	13	093	000	066	043	029	2	338	12	00	00	1
249	0850	322	11	058	000	161	072	070	2	316	06	00	00	1
250	0860	346	12	059	000	107	042	041	2	356	10	00	00	1
251	0910	306	16	058	000	098	084	073	2	022	76	63	86	1
252	0910	288	16	095	000	096	055	038	1	280	08	00	00	1
253	0910	320	16	217	169	140	117	102	2	316	04	23	92	1
254	0900	268	18	087	085	143	090	045	2	266	02	00	00	1
255	0900	262	19	079	123	070	043	021	1	264	02	00	00	1
256	0900	254	19	066	000	072	034	032	1	270	16	36	24	1
257	0910	242	19	064	092	069	032	025	1	204	38	00	00	1
258	0910	228	19	089	120	152	068	064	2	222	06	00	00	1
259	0900	232	19	048	020	063	047	028	2	170	62	00	00	1
260	0900	232	19	044	000	039	025	013	2	286	54	00	00	1
261	0910	224	19	053	036	056	051	033	1	230	06	00	00	1

262	0910	244	19	063	104	043	041	019	2	230	14	00	00	1
263	0910	236	19	076	030	077	074	030	2	316	80	00	00	1
264	0910	236	19	054	000	095	091	028	2	238	02	29	20	1
265	0900	228	19	056	000	092	082	046	2	232	04	00	00	1
266	0900	220	19	049	070	063	045	043	2	306	86	28	48	1
267	0900	224	19	045	073	095	045	022	2	230	06	00	00	1
268	0900	218	19	072	111	095	072	025	1	258	40	00	00	1
269	0900	220	19	078	094	091	055	052	2	246	26	22	17	1
270	0900	228	18	076	023	115	057	046	2	220	08	00	00	1
271	0900	218	20	054	072	083	050	033	2	226	08	18	26	1
272	0900	190	20	070	046	082	062	033	2	198	08	00	00	1
273	0910	192	24	027	076	081	036	027	1	190	02	22	18	1
274	0910	180	22	079	089	077	035	020	1	168	12	00	00	1
275	0900	168	24	070	159	085	071	037	2	154	14	00	00	1
276	0900	178	22	065	000	100	058	034	1	188	10	00	00	1
277	0900	138	20	135	000	152	085	061	2	138	00	00	00	1
278	0900	104	14	161	075	155	106	052	2	098	06	00	00	1
279	0900	100	14	048	078	084	068	030	1	144	44	00	00	1
280	0910	086	14	055	064	155	088	031	1	094	08	30	55	1
281	0910	278	16	064	000	125	093	040	2	082	04	14	24	1
282	0910	030	13	044	020	079	074	029	1	112	82	00	00	1
283	0910	040	12	062	000	234	122	084	1	036	04	00	00	1
284	0900	040	18	054	015	090	076	058	1	088	48	00	00	1
285	0900	350	16	034	000	042	024	017	2	338	12	00	00	1
286	0910	276	15	035	114	176	087	072	1	274	02	00	00	1
287	0910	302	16	064	000	076	058	025	2	308	06	00	00	1
288	0910	298	16	026	050	066	043	017	1	292	06	08	29	1
289	0920	310	21	034	069	051	043	037	1	326	16	38	23	1
290	0920	298	22	057	000	078	076	025	2	226	72	46	38	1
291	0920	328	18	106	782	130	061	050	2	328	00	30	34	1
292	0910	280	25	071	000	083	059	043	2	274	06	00	00	1
293	0910	272	25	052	024	060	050	018	2	260	12	00	00	1
294	0910	266	24	043	000	083	052	023	2	284	18	00	00	1
295	0920	264	30	042	000	064	029	015	2	270	06	15	10	1
296	0920	290	25	038	000	080	042	019	2	288	02	28	19	1
297	0910	278	28	044	000	046	023	007	2	290	12	00	00	1
298	0910	288	19	023	000	116	051	021	2	226	62	22	22	1

299	0910	284	17	056	132	106	058	053	2	250	34	20	42	1
300	0920	282	16	050	118	160	136	067	2	030	52	29	40	1

Glas Allt (NO 253848)

301	1100	242	34	136	187	175	113	063	2	224	18	00	00	1
302	1040	340	22	063	082	135	048	046	2	344	04	00	00	1
303	1040	014	23	052	175	143	074	038	2	030	16	00	00	1
304	1040	358	23	307	000	068	063	032	1	066	68	22	32	1
305	1040	020	22	095	133	105	044	034	2	022	02	12	31	1
306	1040	018	20	093	267	076	037	016	2	004	14	12	24	1
307	1040	008	20	103	000	082	059	023	1	012	04	13	17	1
308	1040	002	20	036	000	088	081	016	2	058	56	04	09	1
309	1040	312	16	037	086	050	032	016	2	044	88	00	00	1
310	1040	348	17	122	165	083	050	028	1	016	28	18	33	1
311	1000	215	15	085	000	112	083	022	2	220	08	28	19	1
312	0980	186	15	083	000	121	082	027	1	188	02	00	00	1
313	0980	192	15	072	000	105	055	023	1	282	90	00	00	1
314	0980	184	15	069	000	079	056	016	1	188	04	00	00	1
315	0970	188	22	069	345	175	110	029	2	184	04	61	28	1
316	0970	194	22	111	200	124	056	039	2	194	00	35	58	1
317	0960	186	20	077	064	084	050	028	1	190	04	00	00	1
318	0950	184	21	115	140	146	122	031	1	212	28	33	20	1
319	0950	194	19	144	000	122	073	036	2	172	22	00	00	1
320	0930	176	16	080	082	192	093	024	1	172	04	47	37	1
321	0920	174	15	150	145	162	086	024	1	178	04	00	00	1
322	0920	162	11	030	360	240	200	057	2	162	00	43	72	1
323	0920	156	16	052	083	083	062	038	1	176	20	00	00	1
324	0910	170	16	090	065	110	089	029	1	176	06	28	33	1
325	0910	166	17	105	066	098	053	014	1	164	02	00	00	1
326	0910	178	16	077	000	143	082	031	2	172	06	24	34	1
327	0910	208	17	047	072	105	066	038	2	214	06	00	00	1
328	0900	186	17	121	000	156	082	038	2	168	18	19	50	1
329	0890	036	15	027	000	104	073	025	2	032	04	00	00	1
330	0890	024	12	053	000	074	024	023	2	024	00	00	00	1
331	0900	034	11	061	000	073	058	021	1	038	04	00	00	1
332	0910	022	14	028	000	055	042	024	1	048	26	00	00	1
333	0910	048	14	044	000	090	053	031	1	046	02	17	23	1

334	0930	006	12	068	000	138	064	028	2	018	12	13	36	1
335	0940	036	14	198	000	105	057	029	1	050	14	09	13	1
336	0950	048	15	111	000	092	062	016	2	058	10	10	13	1
337	0950	046	12	084	000	112	100	050	1	324	82	22	52	1
338	0960	070	12	107	000	135	085	024	2	030	40	14	24	1
339	0960	036	12	054	000	120	067	029	1	056	20	21	26	1
340	0960	074	12	061	000	110	053	047	1	080	06	19	18	1
341	0970	042	15	149	000	128	078	037	2	072	30	31	44	1
342	0970	084	16	047	039	185	078	028	2	088	04	23	37	1
343	0980	076	16	094	000	095	052	032	2	080	04	21	12	1
344	0980	092	16	083	000	162	073	037	2	106	14	26	32	1
345	0990	066	14	033	000	085	053	023	2	112	46	12	23	1
346	0980	036	14	122	000	118	037	035	2	040	04	15	19	1
347	0980	358	13	077	072	095	053	022	2	352	06	00	00	1
348	0990	016	14	043	000	098	040	033	2	026	10	09	37	1
349	0990	030	14	023	000	133	082	024	1	036	06	08	33	1
350	1000	060	14	036	000	174	122	046	1	056	04	23	35	1